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ON THE BEST METHOD OF DEMAGNETIZING IRON IN MAGNETIC TESTING.

By Charles W. Burrows.

The magnetic permeability of a specimen of iron is a function of its previous mechanical, thermal, and magnetic history as well as of its chemical composition. While therefore the magnetic permeability of a given piece of metal may be measured quite accurately at a given instant, in general the very process of measurement adds a new chapter to the history of the metal and may leave it with magnetic properties different from those it had at the beginning of the test. Such a test may be quite misleading as regards the real magnetic properties of the specimen. Hence we are most concerned with those properties and conditions that can be associated and reproduced. Some little space will therefore be devoted to the consideration of the after effects of various details in the history of the magnetic substance, and a plan will be outlined whereby a specimen may be freed from all effects of previous magnetic treatment, and so be brought to a standard condition. We shall thus define a set of normal conditions and specifications under which the specimen is to be tested. When this is done, the permeability becomes a definite physical constant, and may be redetermined at will. All numerical quantities and equations are given in the electromagnetic c. g. s. system of units. Field strength and induction per square centimeter are expressed as so many *units*, although many writers prefer the more distinctive term *gauss*.

THE RESULTS OF EARLIER OBSERVERS.

Considerable work on the influence of previous magnetic treatment and certain other related details on the value of the induction has been done and some of the more important conclusions are here

given. Ewing in his classic work "Magnetic Induction in Iron and other Metals," third edition, 1900, has recorded the following phenomena, most of which are founded on magnetometric measurements either by himself or by earlier investigators.

(1) Demagnetization by hand reversals or by rotating commutator is complete if the maximum current is at least as great as the greatest used since the last demagnetization.[1]

(2) If a force is repeatedly applied and removed, the values of the induction and the residual magnetism form two increasing sequences of numbers whose last terms approach each other.[2] This has been called "molecular accommodation."

(3) During repeated reversals of the same magnetizing force, the change of induction on reversal gradually becomes smaller and finally reaches a constant value.[3]

(4) After the change of induction on slow reversal of current has become constant, a sudden reversal will at first increase the change of induction on reversal, but later reversals make this change smaller than ever.[3]

(5) After application of an intense magnetizing force the tendency to a diminution of the change of induction on repeated reversal of a given magnetizing force has disappeared.[4]

(6) "Creeping" produces a greater induction than is at first shown on the application of the magnetizing force.[5]

In an article entitled "Studies in Magnetic Testing,"[6] Professor Searle gives the results of an extended investigation carried out at the Cavendish Laboratory. An alternating current of 90 cycles controlled by a liquid rheostat furnished the demagnetizing force. Inductions were measured ballistically. The specimens used were samples of transformer iron 4 cm wide, 68.8 cm long, and about 0.035 cm thick, and were so arranged that the magnetic circuit was

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[1] Magnetic Induction, etc., p. 46.

[2] Fromme, Pogg. Ann. Ergbd., **7**; 1875. Wied. Ann., **4**; 1878.

[3] Magnetic Induction, etc., p. 340. My experience seems to indicate that this later decrease is nothing more than a part of the original decrease accelerated perhaps by the sudden reversal.

[4] Magnetic Induction, etc., p. 341. This does not accord with my experience, and is therefore probably found only in certain specimens.

[5] Ewing, Phil. Trans., p. 569, 1885.

[6] G. F. C. Searle, Proc. of Inst. of Elect. Engrs., Part 170, **34**, pp. 55–118; 1904.

a square about 50 cm on a side. The more important conclusions of this paper are here given.

(1) Complete demagnetization is obtained by an alternating current with a frequency of 90 cycles per second, provided the initial demagnetizing force is greater than a certain "critical value."

(2) An imperfect demagnetization results in a lower apparent induction.

(3) The effect of many reversals of a force H_y on the apparent induction due to a small force $H=1$ is modified by many reversals of a force H_x as follows:

(a) If H_x is as large as the critical value, it wipes out the effect of H_y and leaves its own after effect.

(b) If H_x is less than the critical value its effect in raising the apparent induction is less as H_y is greater. In every case it leaves its own after effect.

(c) If H_x is very small, less than one, the after effect in certain cases is to give a lower apparent induction than if H_x were omitted.[7]

(d) If $H_y=0$ the apparent induction may be raised by a small value of H_x.[8]

(4) Many reversals of a force H_x cause a lowering of the apparent induction due to a smaller force H_0, and the lowering increases with H_x.

(5) A constant force superposed upon the force used in determining the induction reduces the apparent induction. A constant force of $H=0.2$ in one case caused a 20 per cent reduction for low values of B.[9]

(6) Virgin iron gives lower values of the apparent induction than demagnetized iron in the lower values of B. In the upper regions the difference disappears. This iron, although it is called virgin because it had experienced no other magnetizing force than the

[7] I have not attempted to verify this. It seems analogous to the decrease in apparent induction noted in some cases when the upper limit of the demagnetizing force was too low.

[8] This is contrary to my experience.

[9] I have noticed a lowering of the apparent induction when the specimen was turned so that the earth's field was parallel to its length.

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earth's field, showed a small initial induction even after careful annealing.[10]

All of the above conclusions have been carefully examined during the present investigation and have been verified except in certain cases, particularly that on the efficiency of demagnetization by alternating current, which will be discussed latter. While these general conclusions do not cover exactly the same ground as the present work yet, with an exception or two, there are no inconsistencies between the earlier work and my own.

DEFINITIONS.

In Fig. 1, B and H are the magnetic induction per square centimeter and magnetizing force, respectively. Then if we start with a piece of virgin iron and apply successively increasing magnetizing forces and note the corresponding inductions, we get a series of points having the line OA as locus. If the magnetizing forces had been negative instead of positive, the symetrical curve OB would have been traced. The positive branch of the curve is commonly called the ascending B–H curve, or simply the ascending curve. Consider the point A on the ascending curve and the corresponding point B on the negative curve. In the course of the ascending curve let the magnetizing force be reversed at the point A. This will cause the point which represents the magnetic state of the iron, or state point, to move along the curve ARB′ where B′ in general is a different point from B. Another reversal will trace the curve B′R′A′ where also A′ is different from A. If the magnetizing force is reversed many times, the path of the state point eventually becomes a closed curve such as is pictured in Fig. 2. The upper tip of this curve defines a pair of values of B and H. If other loops are traced in this manner, but so that each succeeding loop is larger than its predecessor, the locus of the tips of the loops forms the normal curve of ascending reversals, or, as it is sometimes called, the commutation curve. The locus of the lower tips of these same loops is a curve symmetric with this.

[10] I have not been able to obtain any iron free from initial polarization and consequently have no data for virgin iron. The experiment cited is not conclusive, as the small residual magnetization detected would tend to produce the same effect attributed to the fact that the iron is in the virgin state.

Instead of starting with a piece of virgin iron, or with a piece of iron which had been thoroughly freed from all previous polarization, we may start with a specimen which has a residual induction represented by the point P which obviously could lie anywhere on the line RR′. Proceeding as before, we get a system of curves analogous to the preceding but with the symmetry lost. The point corresponding to the center of symmetry has been displaced towards P.

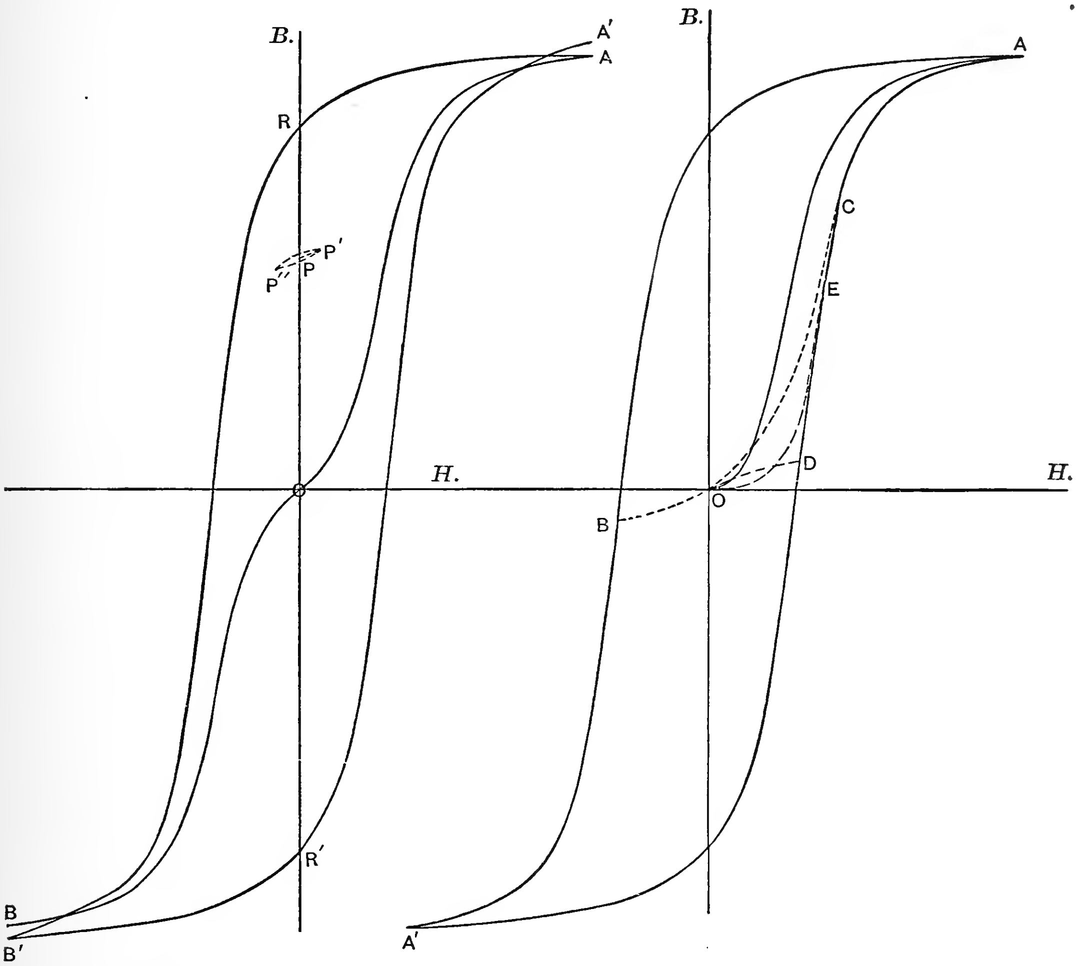

Fig. 1.—*Ideal curve to illustrate the definitions of magnetic properties.*
Fig. 2.—*Ideal curve to illustrate the effect of previous magnetic history on the initial permeability of apparently neutral iron.*

This new center may be so far displaced from the origin that on reversals of small values of H the induction does not change sign, but oscillates between two values of the same sign, such as those represented by P′ and P″. In such a case as this the applied magnetizing force does not determine the absolute induction but only

the amplitude of the oscillation. Instead of comparing the absolute values of B with H, we should rather compare with H the value of this oscillation which is expressible as

$$\frac{1}{2}(B_H - B_{-H})$$

In order to avoid circumlocution and ambiguity the following definitions seem desirable.

The *magnetic induction* is one-half the change of magnetic flux per square centimeter observed on the reversal of a given magnetic force, or

$$\frac{1}{2}(B_H - B_{-H})$$

Permeability is the ratio of this induction to the corresponding magnetizing force, or

$$\mu = \frac{B}{H}$$

The *differential permeability* is the ratio of an infinitesimal change in B to the corresponding change in H. Geometrically it is the tangent of the angle which the tangent to the curve makes with the H axis.

The *hysteresis loop* is the path traced by the state point on a double reversal of a given magnetizing force after sufficient repetition has made the path cyclic.

A *normal hysteresis cycle* is one which is symmetrical about the origin. The induction and permeability are *normal* or *apparent* according as the corresponding hysteresis loops are normal or not.[11]

Iron is in a *neutral state* when it exerts no external field and yields as readily to a positive magnetizing force as to a negative one.

APPARATUS.

In these experiments the magnetic circuit usually consisted of two specimens about 50 centimeters long placed side by side with their adjacent ends joined by suitable wrought-iron yokes. The

[11] The distinction between "normal" and "apparent" is due to Searle (loc. cit.). Rowland (Physical Papers, p. 44) uses "normal" in the sense of "virgin."

magnetizing coils consisted of two sections, each 40 centimeters long, wound with a single layer of 400 turns of No. 22 double cotton covered magnet wire. The secondary coil was uniformly distributed over the middle portion of the specimen. The shearing correction due to end effects is small and has been allowed for in the results. The reduction to absolute values, as well as other details of manipulation, will be described in a subsequent paper. The nature and dimensions of the specimens used are shown in Table I. For each

TABLE I.

Showing the physical constants of the specimens used in this work.

Specimen	Length	Breadth	Thickness	Diameter	Cross section	Specific resistance in micro-ohms
Transformer iron...........	51.0	1.006	*.0355	....	.0357	14.0
Common iron...............	51.0	1.00	.065	....	.065	13.9
Low carbon steel...........	47.1	....	....	.578	.262	13.4
High carbon steel...........	45.8	....	....	.578	.262	18.9

*Calculated from mass and density.

kind of iron and steel two specimens were cut from the same rod or sheet, and though cut from adjoining parts show a small difference magnetically.

CRITERION OF PERFECT DEMAGNETIZATION.

In order to reduce iron to a magnetically neutral state, it must be freed from the effects of previous magnetization. It must not only be freed from all evidences of polarization which would produce an external field and which would be indicated by a suspended magnet or a movable test coil, but also from all internal polarizations which produce no external field. A test coil shows the integrated value of the induction and therefore does not show whether the specimen is in the neutral state. The specimen may be magnetically homogeneous with no external field and yet not be in the neutral state. This appears from Fig. 2. Let the state point be the origin. If the iron is neutral, a small positive force will cause the state point to move along the solid line OA tracing the ascending curve. If,

however, the iron has been previously carried along the path OABO, the state point is again at the origin, but the iron is so influenced by its recent treatment that a small positive force carries the point along the path OC, which initially is above the normal path OA. Again let it be carried along the path OABA′DO. Once more it is at the origin, but with a tendency to move along the path OE with increase of H. This latter path is below the normal path. And so on, with various preliminary paths for the state points, we could cause it to leave the origin in an infinite number of directions which would mean an infinite number of initial permeabilities. And yet in each of these cases an external magnet or a movable test coil would give no indication of the inherited tendencies of the specimen.

In general, if the origin is made the lower tip of a secondary hysteresis loop, its initial permeability in the ascending curve is less than normal. If, however, the origin is near the middle of the ascending branch of a secondary hysteresis loop, the initial permeability is greater than normal. These facts show that the ordinary criteria for perfect demagnetization are unsatisfactory and indicate that no test is possible which will not modify the neutral state if it should exist.

Before a satisfactory criterion of perfect demagnetization can be determined upon, it is necessary to know something of the nature of the influence a residual induction has on the apparent induction. With this in view, the following experiment was carried out: A specimen was demagnetized as thoroughly as might be and its apparent induction measured. Then the specimen was subjected momentarily to a magnetizing force which would give it a certain residual induction. After the removal of this force the apparent induction for the same force as before was determined. These operations were repeated with successively increasing polarizing forces. The results are shown graphically in Fig. 7. From this curve it is seen that as the polarizing force increases the resultant induction decreases. Applied to Fig. 1, this means that the small cyclic loop P′P P″ becomes more nearly parallel to the H axis as P recedes from this axis. In consequence of this fact, which holds in every case examined, *the criterion of perfect demagnetization is that the induction shall be a maximum.*

PREVIOUS METHODS OF DEMAGNETIZATION.

Many methods have been employed to remove residual polarizations and to reduce the specimen to a magnetically neutral state. The method most generally employed is that of *descending reversals* in which the demagnetizing force is repeatedly reversed while it is gradually decreased in value. The reversals may be made by hand with an ordinary reversing switch, by a rotating commutator driven either by hand or by power, or by an alternating current. The reduction of current may be made by any form of rheostat. The liquid resistance has found favor in many quarters, chiefly because it gives a continuous variation of current and not a series of steps, as in most types of rheostats.

Ewing[12] suggests a *potential slide*, made as follows: A tall glass jar is filled with a dilute solution of zinc sulphate. Three blocks of amalgamated zinc are fitted in the jar—one lying on the bottom, one fixed at the top, and the third hung between them by a cord, which passes over a pulley above to a little winch. The battery is connected to the fixed blocks, and the magnetizing coils to one fixed block and to the movable block. By altering the position of the movable zinc block the electromotive force applied to the magnetizing coils may be varied. Reversals were made by a rotating commutator worked by hand.

Searle[13] used an alternating current of 90 cycles supplied from the city mains. His resistance consisted of a narrow glass trough containing dilute copper sulphate solution, and furnished with two copper electrodes, one of which was movable. By tilting the trough so that one end was dry the current could be reduced to a very small value.

CURRENT REGULATION.

In this investigation all the available methods of current control were tried. Several kinds of liquid resistances were used. In some of these the electrodes were moved apart so as to give a longer path through the liquid. In others the liquid was removed from the containing vessel. This was accomplished in several ways—by tilting the vessel, by siphoning off the liquid to another vessel, and again by allowing the liquid to run out through a stopcock in the

[12] Magnetic Induction, etc., p. 44.

[13] Proc. Inst. of Elect. Engrs., **34**, p. 61; 1904.

bottom of a tall cylindrical vessel. The latter was the most satisfactory of the liquid type. The ordinary forms of rheostats, with fixed steps, controlled by dial sliding contacts, by plugs, or by links and mercury cups, were tried. Another form used was the Kelvin rheostat, in which the wire is wound from a drum of conducting material to an insulating drum. This gives uniform variation, and is easily controlled, but is laborious. The most satisfactory rheostat used was a cylinder of slate wound with bare wire, having a sliding contact moving parallel to the axis of the cylinder. Several of these resistances of different sizes of wire are connected in series and are highly satisfactory.

Current decrease was also effected by changing the applied electromotive force while keeping the resistance constant. In this case the demagnetizing circuit was connected to two points of an adjustable resistance through which a current was flowing. This method was found to offer no advantage over the preceding, but has some obvious disadvantages.

Early in the investigation it became apparent that the efficiency of demagnetization depended not so much on the total time consumed as on the rate at which the demagnetizing current was reduced. To test this point the demagnetizing current was reduced successively in three different ways. First, so that the rate of increase of resistance was constant; second, so that the rate of decrease of current was approximately constant, and, third, so that the rate of decrease of induction was constant. This last method gave the best results and has been followed in all the later work.

The electromotive force to be used is determined largely by the requirements of the induction measurements to be made after the demagnetization. For these the first requirement is constancy, which is best obtained by a storage battery furnishing no other current. A relatively high voltage is advantageous, because the higher the regulating resistance the easier is the regulation and the lower the time constant of the circuit. These two factors are closely connected with rapidity of the measurements and the accuracy of results. On the other hand, a low voltage means less trouble from arcing at the commutator and less outlay for battery and the extra resistance needed. Twenty volts is an intermediate value, which meets all requirements and has been used in this series of experiments.

POLARIZATION EFFECT.

It is well at the outset to determine something of the nature of the polarization effects which are to be removed by the process of demagnetization. To this end several specimens of iron were examined after having been exposed to different magnetic treatments. The iron was first demagnetized as well as might be and its apparent induction determined for a series of values of the magnetizing force. Then the iron was subjected to a strong magnetizing force of 100 units (gausses) after which the induction was redetermined. This polarizing force was applied and removed several times, but it was not reversed in this first comparison. The results of this experiment are shown numerically in Tables II, III, IV, and V, and

TABLE II.

To illustrate the effect of the residual polarization due to a force of 100 on the apparent induction in annealed transformer iron.

Magnetizing force	Induction after demagnetization	Apparent induction when polarized	Polarization effect	Per cent polarization effect	$\mu=\frac{B}{H}$
.1	68	26	42	62	680
.2	192	67	125	65	960
.3	370	130	240	65	1260
.4	670	230	440	66	1670
.5	1290	480	810	63	2580
.6	1680	720	960	57	2800
.7	2570	1380	1190	46	3670
.8	3370	2510	860	26	4210
.9	4300	3700	600	14	4780
1.0	5130	4750	380	7	5130
1.1	5710	5360	350	6	5170
1.2	6730	6490	240	4	5230
1.3	6880	6750	130	2	5290
2.0	8880	8880	0	0	4440
3.0	10750	10750	0	0	3580
5.0	12750	12750	0	0	2550
10.0	14620	14620	0	0	1460
15.0	15280	15280	0	0	1020

Plotted in Fig. 3.

TABLE III.

To illustrate the effect of the residual polarization due to a force of 100 on the apparent induction in common sheet iron.

Magnetizing force	Induction after demagnetization	Apparent induction when polarized	Polarization effect	Per cent polarization effect	$\mu=\frac{B}{H}$
1	263	97	166	63	263
2	1314	496	818	62	657
3	3770	3130	640	17	1257
5	7890	7730	160	2	1580
7	10270	10130	140	1	1467
10	12170	12160	10	0	1217
15	13610	13610	0	0	907

Plotted in Fig. 5.

TABLE IV.

To illustrate the effect of the residual polarization due to a force of 100 on the apparent induction in low carbon Bessemer steel.

Magnetizing force	Induction after demagnetization	Apparent induction when polarized	Polarization effect	Per cent polarization effect	$\mu=\frac{B}{H}$
1	190	90	100	53	190
2	680	370	310	46	340
3	1930	1460	470	24	640
4	4150	3670	480	12	1040
5	6790	6300	490	7	1360
7	9990	9740	250	3	1440
10	12470	12470	0	0	1250
15	14170	14170	0	0	940

Plotted in Fig. 4.

graphically in Figs. 3, 5, 4, and 6. From these data and curves it is to be noted that the four specimens of iron show several common characteristics.

(1) The induction after demagnetization is greater than the apparent induction after the intense polarization. The difference between

TABLE V.

To illustrate the effect of the residual polarization due to a force of 100 on the apparent induction in high carbon crucible steel.

Magnetizing force	Induction after demagnetization	Apparent induction when polarized	Polarization effect	Per cent polarization effect	$\mu = \frac{B}{H}$
1	108	54	54	50	108
2	249	125	124	50	124
3	405	210	195	48	135
5	780	440	340	44	156
10	2980	2600	380	13	298
15	6680	6610	70	1	445
30	10650	10650	0	0	335
40	11670	11670	0	0	292

Plotted in Fig. 6.

these two inductions is a quantity which comes up again and again and may be called the "polarization effect." The polarization effect is a measure of completeness of the previous demagnetization. If the demagnetization is perfect the polarization effect is zero. The first point noted then is that the polarization effect is always positive.

(2) As the magnetizing force under which the apparent induction is measured increases, the polarization effect at first increases, then passes through a maximum, and finally decreases to zero.

(3) The point at which the polarization effect is a maximum is somewhat lower than the point of maximum permeability and near the point where the differential permeability is a maximum.

(4) The point at which the polarization effect vanishes is somewhat above the point of maximum permeability. This vanishing point is a critical point magnetically. We shall therefore denote the corresponding force and induction as "critical demagnetizing force"[14] and "critical induction."

(5) While the initial polarization effect initially increases, the normal induction increases so much faster that the percentage polarization effect decreases continuously with increasing magnetizing force.

To test the nature of this polarization effect still further, the

[14] Searle calls this "critical magnetic force."

annealed transformer iron was demagnetized and subjected momentarily to successively increasing polarizing forces. After each application of the polarizing force a magnetizing force of 0.5 was applied and slowly reversed several hundred times. After the iron had reached a cyclic condition the apparent induction was measured.

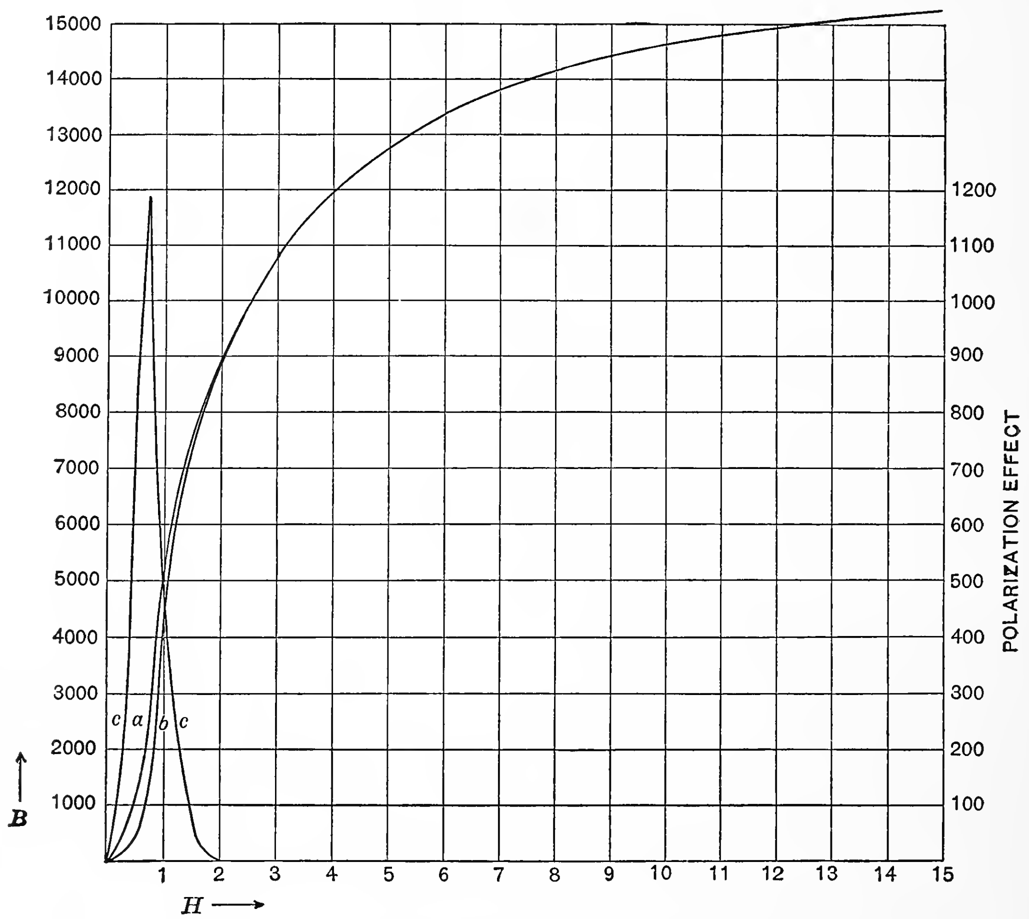

Fig. 3.—*Showing characteristics of annealed transformer iron.*

(Numerical data in Table II.)

(a) Normal *B–H* curve.
(b) Apparent *B–H* curve after intense polarization.
(c) Polarization effect magnified 10-fold relatively to the *B–H* curves.

The results are shown numerically in Table VI and graphically in Fig. 7. In the curve the apparent induction is plotted against the polarizing force. The same figure may be considered as a curve of polarization effects, for the distance of the curve below the line of normal induction is the polarization effect. It is to be noted that the curve of polarization effect plotted against polarizing force

TABLE VI.

Showing the influence of various polarizing forces on the apparent induction.

Polarizing force	Apparent induction	Polarization effect	Polarization effect ÷ polarizing force
.5	1290	0	0
.6	1285	5	8
.7	1260	30	43
.8	1210	80	100
.9	1145	145	161
1.0	1095	195	195
1.5	925	365	243
2.0	820	470	235
3.0	680	610	203
4.0	605	685	171
5.0	555	735	147
10.0	490	800	80
20.0	480	810	40

Plotted in Fig. 7.

resembles the ordinary *B–H* curve with initial slope gradual, then passing through a maximum and finally becoming horizontal. However, for polarizing forces between zero and the force under which the apparent induction is measured, the curve is horizontal. This does not mean that polarizing forces less than the magnetizing force studied are without any effect on the iron, but that any such effect is completely wiped out by the repeated reversals of the chosen magnetizing force.

Certain experiments on the effects of imperfect demagnetization seemed to indicate that the data recorded above do not represent the maximum possible polarization effects for the given polarizing forces. To test this point the polarizing force was applied in different ways. Experiment showed that a given force left a greater residual polarization effect if it were reversed several times than if it were simply applied and removed the same number of times. The data of Table VII substantiate this conclusion. The last column of this table shows the difference in polarization effects under these

two methods of procedure. It is noticeable that these differences are very roughly porportional to the corresponding original polarization effects. This shows that the change due to the reversals of the polarizing force is uniformily distributed, and that the general conclusions as to the nature of the polarization effect hold in this case as well as in the former.

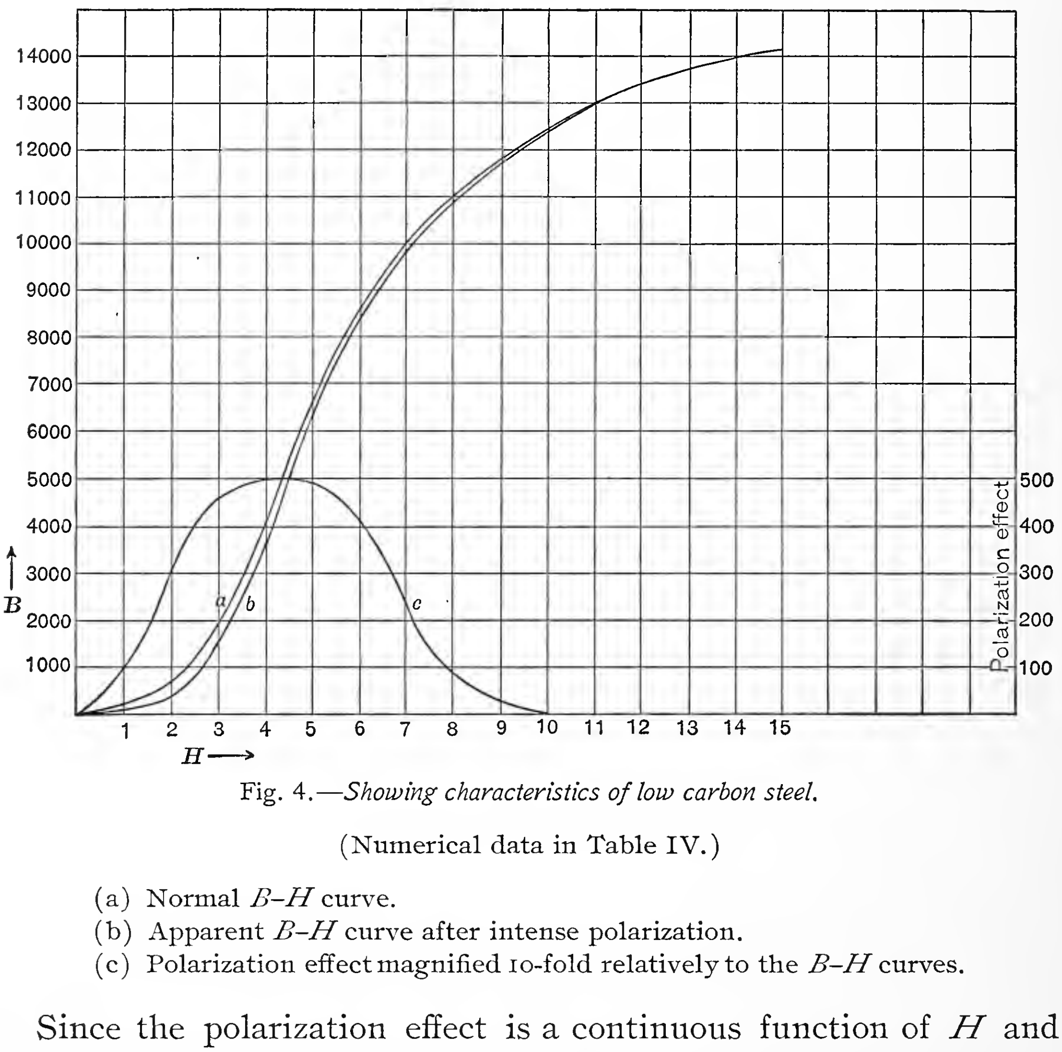

Fig. 4.—*Showing characteristics of low carbon steel.*

(Numerical data in Table IV.)

(a) Normal B–H curve.
(b) Apparent B–H curve after intense polarization.
(c) Polarization effect magnified 10-fold relatively to the B–H curves.

Since the polarization effect is a continuous function of H and has a maximum at the same value of H, though of different magnitude in the two methods of polarizing used, it was assumed that the polarization effect would be a maximum at the same value of H under all conditions, and when it vanished at this force it would have vanished for all other magnetizing forces. This is a rather bold assumption; but it furnishes a good working basis and economizes time, as it allows the characteristics at a single point to typify

the characteristics of a whole range of points. This assumption is later justified for all the ordinary methods of demagnetization.

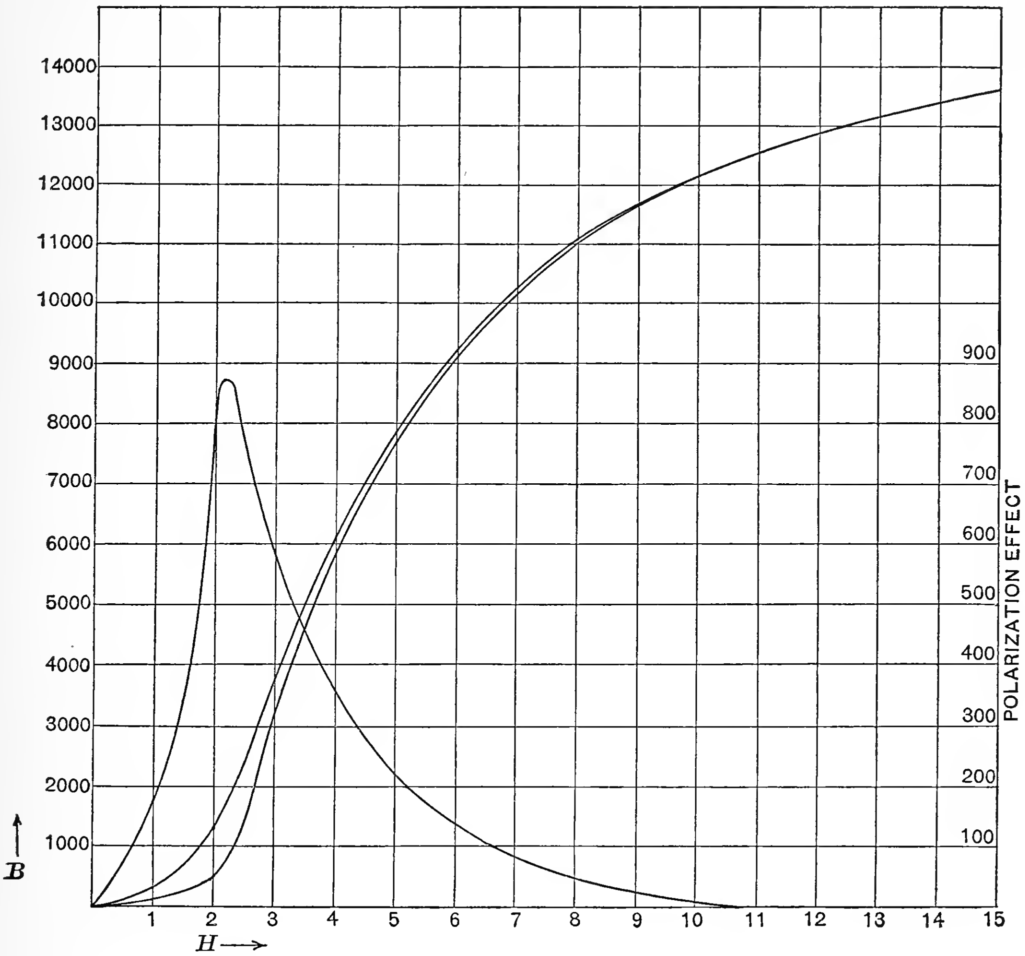

Fig. 5.—*Showing characteristics of common sheet iron.*
(Numerical data in Table III.)

(a) Normal *B–H* curve.
(b) Apparent *B–H* curve after intense polarization.
(c) Polarization effect magnified 10-fold relatively to the *B–H* curves.

UPPER LIMIT OF THE DEMAGNETIZING FORCE.

It has been assumed in nearly all earlier work [15] that a necessary condition for perfect demagnetization is that the demagnetizing current must carry the iron from an induction greater than any previous one it has experienced down to a vanishingly small one. The question at once arises as to whether a somewhat smaller range

[15] See (1) on p. 206 and (1) on p. 207

might not be equally successful in wiping out the effects of previous polarization.

To determine the maximum value of a necessary yet sufficient demagnetizing force the following experiment was carried out: The specimen was first strongly magnetized by a force of 100 to

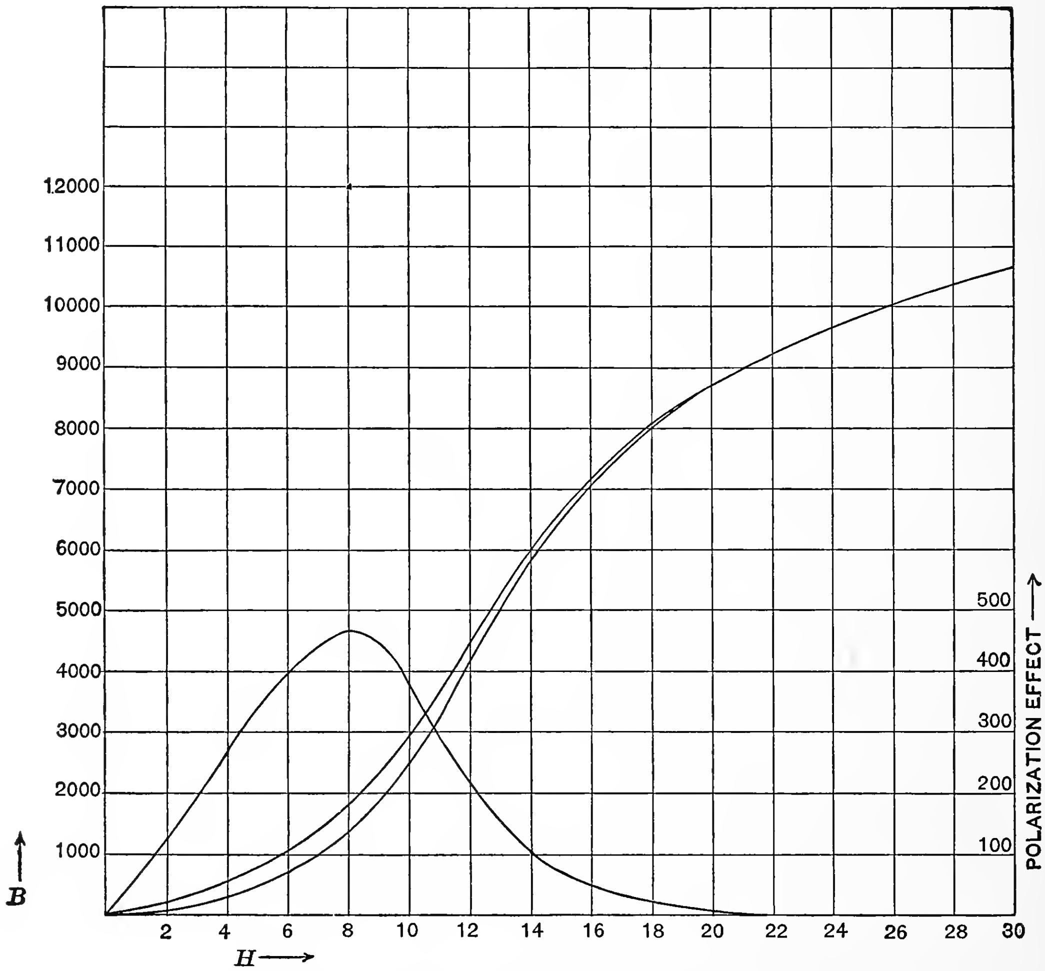

Fig. 6.—*Showing characteristics of high carbon steel,*

(Numerical data in Table V.)

(a) Normal *B–H* curve.
(b) Apparent *B–H* curve after intense polarization.
(c) Polarization effect magnified 10-fold relatively to the *B–H* curves.

insure a considerable initial polarization. Then it was demagnetized from a certain value of the demagnetizing force down to a vanishingly small force. The cyclic apparent induction was then measured for the value of *H*, at which the previously observed

polarization effect was a maximum. After this measurement the specimen was again strongly magnetized as before, demagnetized from a second maximum down to the same vanishingly small force, and finally the cyclic apparent induction was measured for the same magnetizing force as before. This process was repeated for a series

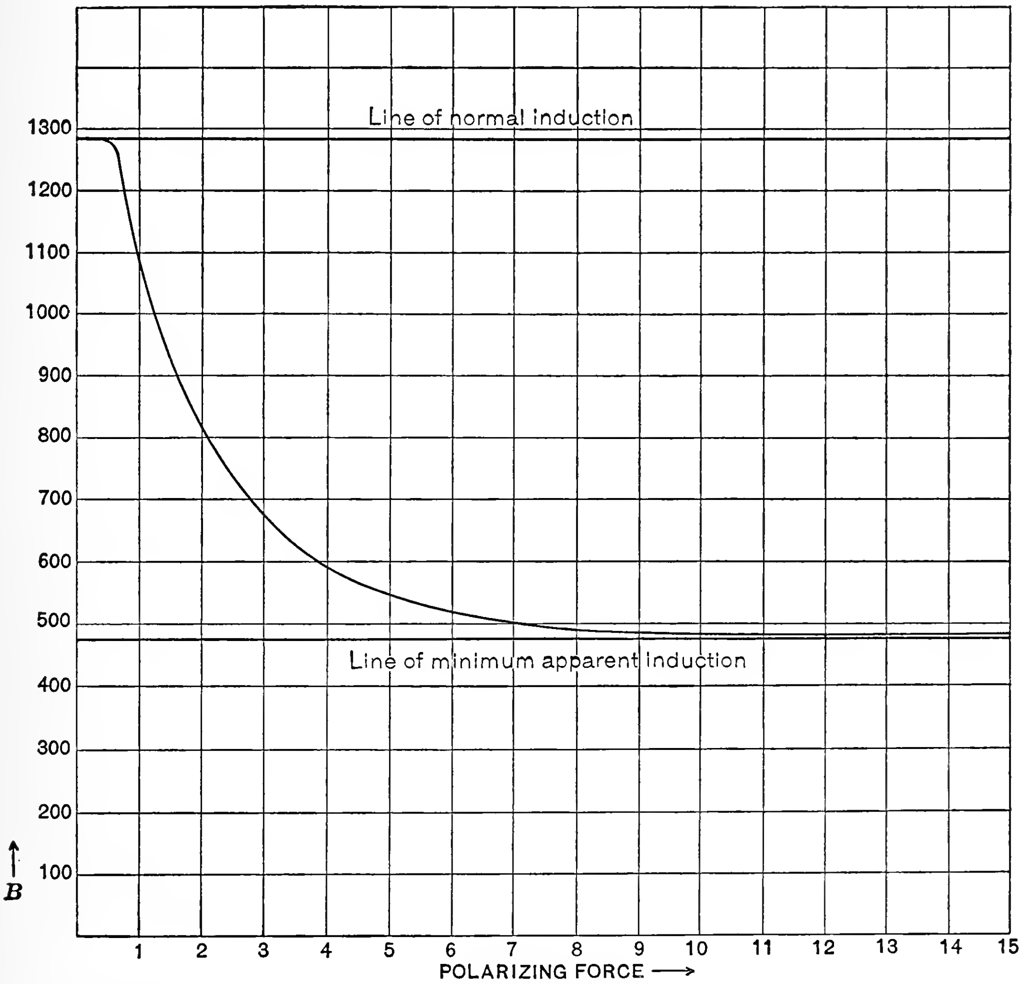

Fig. 7.—*Showing the relation between the polarizing force and the apparent induction in annealed transformer iron for $H=0.5$.*

(Numerical data in Table VI.)

of values of the maximum demagnetizing force. The results of these experiments are shown graphically in curves marked "curve of upper limits" in Figs. 8, 9, and 10, where the maximum demagnetizing forces are plotted as abscissæ and the apparent inductions as ordinates. From these three curves the following characteristics may be noted:

(1) For maximum demagnetizing forces greater than the critical demagnetizing force the curve is parallel to the horizontal axis. This indicates that the demagnetization is not improved by carrying the demagnetizing force beyond this *critical demagnetizing force.*

(2) For maximum demagnetizing forces less than the magnetic force used to determine the apparent induction the curve is again horizontal. This shows that such demagnetization produces no effect that the simple reversals of the magnetizing force used in determining the induction would not accomplish.

TABLE VII.

Showing that the polarizing effect of a field of 100 is greater on reversal than on simple make and break.

Magnetizing force	Normal induction	Polarization effect of make and break	Polarization effect of reversals	Difference
.3	370	240	290	50
.4	670	440	520	80
.5	1290	810	910	100
.6	1680	960	1080	120
.7	2570	1190	1310	120
.8	3370	860	1050	190
.9	4300	600	730	130
1.0	5130	380	500	120
1.2	6730	240	330	90
1.4	6950	90	110	20
1.6	7610	30	30	0
2.0	8880	0	0	0
3.0	10750	0	0	0

(3) The two horizontal portions are connected by a smooth curve, indicating that over this range the demagnetization is more or less imperfect but is approaching completeness very rapidly with increase of maximum demagnetizing force.

(4) A comparison of the curves for the soft annealed transformer iron, the moderately hard low carbon steel, and the hard high carbon steel shows that the steepness of this sloping portion of the curve and the sharpness of the bends at its upper and lower extremities decreases as the hardness of the iron increases.

TABLE VIII.

Showing the apparent induction in annealed transformer iron as influenced by the upper limit of the demagnetizing force.

Limits of demagnetizing force	3 (or more)—.2	2—.2	1—.2	.5—.2	No demagnetization
Time interval	92.4	72.4	99	91.8	
Number of cycles	145	107	154	135	
	B	*B*	*B*	*B*	*B*
$H=$ .3	370	360	320	220	130
.4	670	670	630	360	230
.5	1290	1290	1210	740	480
.6	1680	1680	1570	770	720
.7	2570	2570	2340	1530	1380
.8	3370	3370	2990	2460	2510
.9	4300	4300	3780	3580	3700
1.0	5130	5130	4620	4650	4750
1.2	6730	6730	6370	6370	6490
1.4	6950	6950	6720	6710	6860
1.6	7610	7610	7390	7390	7580
2.0	8880	8880	8730	8730	8880
3.0	10750	10750	10750	10750	10750

TABLE IX.

Showing polarization effects (calculated from Table VIII).

Limits of demagnetizing force	3—.2	2—.2	1—.2	.5—.2	No demagnetization
.3	0	10	50	150	240
.4	0	0	40	310	440
.5	0	0	80	550	810
.6	0	0	110	910	960
.7	0	0	230	1040	1190
.8	0	0	380	910	860
.9	0	0	520	720	600
1.0	0	0	510	480	380
1.2	0	0	360	360	240
1.4	0	0	230	240	90
1.6	0	0	220	220	30
2.0	0	0	150	150	0
3.0	0	0	0	0	0

TABLE X.

Showing the apparent induction in common sheet iron as influenced by the upper limit of the demagnetizing force.

Limits of demagnetizing force	10–1	7–1	5–1	No demagnetization
Time interval	54	42	32	
Number of cycles	84	64	48	
H	B	B	B	B
1	263	255	255	97
2	1314	1304	1304	496
3	3770	3750	3740	3130
5	7890	7810	7700	7730
7	10270	10200	10170	10130
10	12170	12170	12160	12160
15	13610	13610	13610	13610

TABLE XI.

Showing polarization effects (calculated from Table X).

Limits of demagnetizing force	10–1	7–1	5–1	No demagnetization
H=1	0	8	8	166
2	0	10	10	818
3	0	20	30	640
5	0	80	190	160
7	0	70	100	140
10	0	0	10	10
15	0	0	0	0

TABLE XII.

Showing the apparent induction in low carbon steel as influenced by the upper limit of the demagnetizing force.

Limits of demagnetizing force	15—.2	10—.2	5—.2	No demagnetization
Time interval	70	70	49	
Number of cycles	100	100	70	
	B	*B*	*B*	*B*
H= 1	190	190	183	90
2	680	675	667	370
3	1930	1920	1897	1460
4	4150	4130	3990	3470
5	6790	6745	6590	6300
6	9140	9100	9000	8670
7	9990	9960	9920	9740
8	11070	11060	11040	10950
9	11880	11870	11870	11820
10	12470	12460	12470	12460
15	14170	14170	14170	14170

TABLE XIII.

Showing polarization effects (calculated from Table XII).

Limits of demagnetizing force	15—.2	10—.2	5—.2	No demagnetization
1	0	0	7	100
2	0	5	13	310
3	0	10	33	470
4	0	20	160	480
5	0	45	200	490
6	0	40	140	370
7	0	30	70	250
8	0	10	30	120
9	0	10	10	60
10	0	10	0	10
15	0	0	0	0

The preceding applies to a single value of the magnetizing force. To show that this is typical, and to get further light on the nature of the polarization effect under different degrees of completeness in the demagnetization, the full range of points was taken for a few different sets of magnetizing limits. The data for the apparent inductions after various demagnetizations in which the upper limit

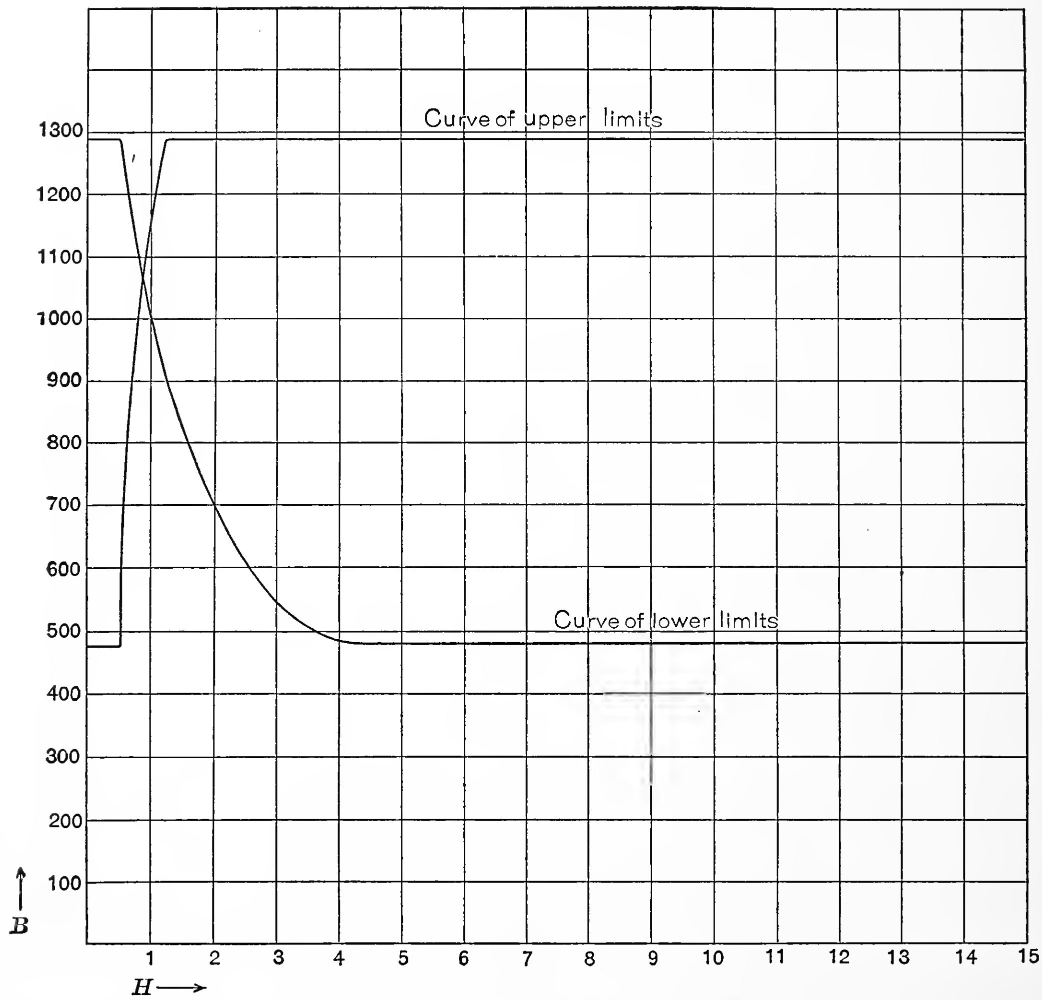

Fig. 8.—*Showing the influence of the upper and lower limits of the demagnetizing force on the apparent induction of annealed transformer iron for $H=0.5$.*

alone was altered are given in Tables VIII, X, and XII. The corresponding data for the polarization effects are more instructive and are given in Tables IX, XI, and XIII. From these six tables the following conclusions may be drawn:

(1) The demagnetization is complete throughout the whole range if the upper limit is at least as great as the critical demagnetizing force.

(2) If the maximum demagnetizing force is less than the critical demagnetizing force, the demagnetization is in general incomplete, and the incompleteness extends over practically the whole region from the lowest values of the magnetizing force up to the critical value. This region may be called the *domain* of the polarization effect.

Fig. 9.—*Showing the influence of the upper and lower limits of the demagnetizing force on the apparent induction of high carbon steel for $H=10$.*

(3) The polarization effect increases as the maximum demagnetizing force decreases, but preserves its general characteristics as described above.

(4) In certain cases the polarization effect is greater after a feeble demagnetization than without any demagnetization.[16] Tables IX and XI for the transformer iron and the common sheet iron, resepctively, show this very clearly. This phenomenon occurs at or below the point of maximum permeability. It was this peculiar increase of polarization that suggested the comparison of polarization effects

[16] Cf. Searle's conclusion, 3c on p. 207.

after repeated simple make and break, with those after reversals. A comparison with those results in Table VII will show that the increased polarization effect is still less than the maximum observed on reversal.

Some further observations on the effect of varying the upper limit of the demagnetizing force will be made under the discussion of the influence of frequency of an alternating current demagnetization on the polarization effect.

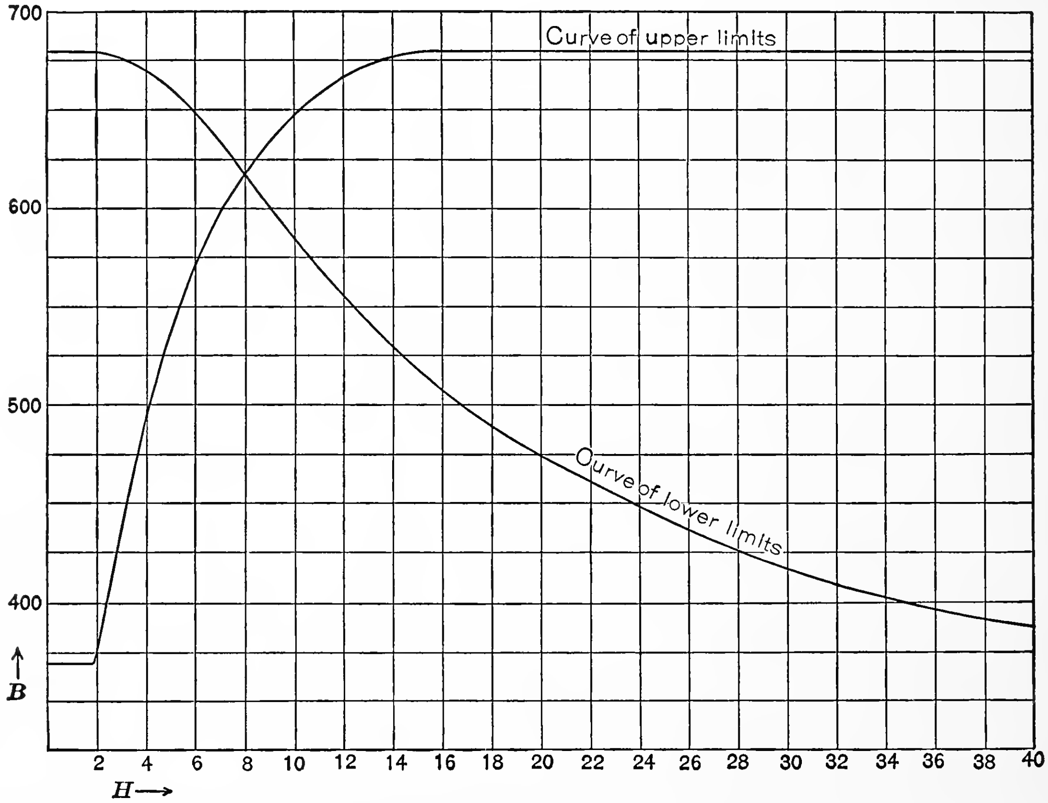

Fig. 10.—*Showing the influence of the upper and lower limits of the demagnetizing force on the apparent induction of low carbon steel for $H=2$.*

LOWER LIMITS OF THE DEMAGNETIZING FORCE.

Having settled upon a proper value for the upper limit of the demagnetizing force, it now remains to determine the necessary and sufficient final minimum value of this force. For this purpose an experiment similar to the preceding was carried out. The specimen was polarized initially as before. The demagnetization was carried from a point well above the critical demagnetizing force down to a certain minimum value. Finally the cyclic apparent induction was

measured for the same force as in the preceding experiment. These operations were repeated, modifying only the final minimum value of the demagnetizing force. The results of this experiment are shown graphically in the curves marked "curve of lower limits" in Figs. 8, 9, and 10. The minimum value of the demagnetizing force is plotted as abscissa and the corresponding cyclic apparent induction as ordinate. Both coordinates are plotted to the same scale as in the curve of upper limits. From these curves the following conclusions may be drawn:

TABLE XIV.

Showing the apparent induction of annealed transformer iron as influenced by the lower limit of the demagnetizing force.

Limits of demagnetizing force	15—.32	15—.5	15—1.15	15—2.6	No demagnetization
Time interval	95.8	97.8	66	60	
Number of cycles	160	155	104	96	
H	*B*	*B*	*B*	*B*	*B*
.3	370	352	250	160	130
.4	670	660	450	340	230
.5	1290	1290	990	645	480
.6	1680	1680	1470	1000	720
.7	2570	2570	2420	1800	1380
.8	3370	3370	3180	2700	2510
.9	4300	4300	4270	3870	3700
1.0	5130	5130	5110	5030	4750
1.2	6730	6730	6730	6690	6490
1.4	6950	6950	6950	6950	6860
1.6	7610	7610	7610	7610	7580
2.0	8880	8880	8880	8880	8880
3.0	10750	10750	10750	10750	10750

(1) For values of lower limit of the demagnetizing force less than the magnetizing force which produces the apparent induction, the curve is a horizontal line. This indicates that the demagnetization is not improved by carrying the demagnetizing force below the lowest magnetizing force to be studied.

(2) For values of the lower limit considerably greater than the critical demagnetizing force the curve is a horizontal straight line and indicates that the demagnetizing force does not modify the previously existing polarization effect; at least it does not modify that portion of it which repeated reversals of the given magnetizing force do not eliminate.

(3) Between the two horizontal portions is a continuous sloping curve, which indicates a partial demagnetization which increases in completeness very rapidly as the lower limit of the demagnetizing force decreases.

TABLE XV.

Showing the apparent induction of common sheet iron as influenced by the lower limit of the demagnetizing force.

Limits of demagnetizing force	15–1	15–2	15–3	15–5	15–7	No demagnetization
Time interval	38	37	31	22	17	
Number of cycles	56	52	48	32	26	
H	*B*	*B*	*B*	*B*	*B*	*B*
1	263	255	197	151	120	97
2	1314	1314	1224	890	820	496
3	3770	3770	3770	3350	3220	3130
5	7890	7890	7890	7890	7860	7730
7	10270	10270	10270	10270	10270	10130
10	12170	12170	12170	12170	12170	12160
15	13610	13610	13610	13610	13610	13610

(4) A comparison of the curves for three grades of iron and steel shows that the steepness of the curved portion and the sharpness of the bends at the upper and lower extremities decrease as we pass from the softer to the harder material. The lower horizontal portion occurs at extremely high values in the hard material. (Figs. 9 and 10.)

To justify the above conclusions drawn from measurements made at a single value of the magnetizing force, and to investigate further the nature of the polarization effect several complete apparent induction curves were obtained under different details of demagnetization.

These complete data are given in Tables XIV, XV, and XVI. From these data the preceding conclusions are justified, and the following generalization appears: *If the demagnetization is carried from the critical demagnetizing force down to a certain point, the demagnetization is complete for all values above the final demagnetizing force. For magnetizing forces below this final value of demagnetization the demagnetization is incomplete, and the incompleteness is greater the greater the interval between the final demagnetizing force and the magnetizing force used to produce the induction desired.*

TABLE XVI.

Showing the apparent induction of low carbon steel as influenced by the lower limit of the demagnetizing force.

Limits of demagnetizing force	15—.2	15—2.5	15—3	15—5	No demagnetization
Time interval	75	73	167	156	
Number of cycles	83	80	200	180	
H	*B*	*B*	*B*	*B*	*B*
1	190	185	175	152	90
2	680	680	668	566	370
3	1930	1930	1930	1795	1460
4	4150	4150	4150	4150	3470
5	6790	6790	6790	6790	6300
6	9140	9140	9140	9140	8670
7	9990	9990	9990	9990	9740
8	11070	11070	11070	11070	10950
9	11880	11880	11880	11880	11820
10	12470	12470	12470	12470	12460
15	14170	14170	14170	14170	14170

EDDY CURRENTS—THEORY.

If we use an alternating current in demagnetizing, we must consider the shielding effect which the eddy currents exert on the interior of the specimen. The magnetizing force at any point is the resultant of the force due to the current in the wire and the force due to the eddy currents in the specimen. The calculation of this

force presents great difficulties unless certain simplifying assumptions are made. Heaviside[17] in a paper entitled "The Induction of Currents in Cores," gives a solution for the special case of a round rod of constant permeability magnetized by a simple harmonic force. In this case the force at any point of the specimen is a function of

μ = the permeability.
ρ = the specific resistance.
N = the frequency.
r = the distance of the point from the axis.

If we let $x=\frac{8\pi^2\mu N}{\rho}$ the resultant magnetic force at any point is

$$H=AM+BN,$$

where A and B are constants, and

$$M=\frac{1}{2}\left\{J_o(r\sqrt{-ix})+J_o(r\sqrt{ix})\right\}$$
$$=1-\frac{x^2r^4}{2^2.4^2}+\frac{x^4r^8}{2^2.4^2.6^2.8^2}-\ldots\ldots$$
$$N=\frac{1}{2i}\left\{J_o(r\sqrt{-ix})-J_o(r\sqrt{ix})\right\}$$
$$=\frac{xr^2}{2^2}-\frac{x^3r^6}{2^2.4^2.6^2}+\frac{x^5r^{10}}{2^2.4^2.6^2.8^2.10^2}-\ldots\ldots$$

The maximum value of H at any point in the core is proportional to

$$\sqrt{M^2+N^2}$$

By squaring the expressions for M and N, and adding, we have

$$M^2+N^2=J_o(r\sqrt{-ix})J_o(r\sqrt{ix})$$
$$=1+\frac{2y}{2^2.4^2}\left(1+\frac{3y}{6^2.8^2}\left(1+\frac{3\frac{1}{3}y}{10^2.12^2}\left(1+\frac{3\frac{1}{2}y}{14^2.16^2}\left(1+\frac{3\frac{3}{5}y}{18^2.20^2}\left(1+\ldots\right.\right.\right.\right.\right.$$

where $y=x^2r^4$.

Since every term of the series is positive, the amplitude increases as we pass from the axis outward. To get some idea of the relative

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[17] Electrical Papers, Vol. I, p. 353 ff.

magnitude of the amplitudes at various distances from the axis, I have calculated values of $\sqrt{M^2+N^2}$ for different values of y. These calculated values are shown graphically in Fig. 25, where $\sqrt{M^2+N^2}$ is plotted as abscissa and y as ordinate. $\sqrt{M^2+N^2}$ is the ratio of the amplitude for a given value of y to the amplitude at the center where y is zero.

Putting

$$\mu = 1000$$

$$\rho = 10000 \text{ c. g. s. units } (=10 \text{ micro-ohms})$$

$$N = 60$$

we have

$$y = x^2 r^4$$

$$= \left[\frac{8\pi^2 \mu N}{\rho}\right]^2 r^4$$

$$y = 224000\ r^4$$

The last equation is plotted on the left half of Fig. 25 in connection with the curve of amplitudes; y is plotted upward on the same axis for both curves. The distance from the center r is plotted to the left. Curves are drawn also for $\mu=500$ and $\mu=2000$. From this figure the relative amplitudes at any distance from the axis may be obtained, subject of course to the conditions stated above. Apply this to a rod of the dimensions of the low carbon rod already used. If $\mu=500$, a point on the surface, $r=0.29$ cm, corresponds to the point P on the (y, r) curve and Q on the $(\sqrt{M^2+N^2}, y)$ curve, so that at the surface of the rod the maximum induction is 4.4 times its value at the axis. For $\mu=1000$ the maximum induction at the boundary is 14 times the value at the axis. The induction has half the boundary value at $r=0.235$ cm, showing that the resultant force, and consequently the induction, is much greater in the outer layers of the rod. The flatness of the (y, r) curve for small values of r shows that the force and flux are nearly uniform near the axis of the rod. This variation of the resultant magnetic force throughout the cross section of the rod increases with increase

of radius, frequency, conductivity, and permeability, and leads us to expect incomplete demagnetization by alternating currents unless relatively large currents are used. The following experiments show that the observed facts are in harmony with the theory.

FREQUENCY OF THE DEMAGNETIZING CURRENT.

In determining the effects on the resultant apparent induction of the rate of reversal of the demagnetizing current, various samples of iron were tested using (a) alternating current of a wide range of frequencies and (b) direct current reversed by a rotating commutator or by a hand commutator. A special harmonic generator set capable of yielding individually any of the first eight odd harmonics to a fundamental frequency of 60 cycles per second, was used to produce frequencies of 900, 780, 660, 540, 420, 300, 180, and 60. Separate machines were used to generate frequencies of 120, 90, and 60 cycles per second. By reducing the speed of the 60 cycle generator frequencies of 30 and 20 cycles per second were obtained. A motor-driven rotating commutator reversed a direct current so as to furnish frequencies ranging from 15 cycles to 1 cycle per second. An ordinary reversing switch, worked by hand, gave frequencies of from 5 cycles down to one-half cycle per second. By these means a wide range of frequencies extending from 900 cycles per second down to one-half cycle per second was obtained. As in the earlier work the specimens used were annealed transformer iron, mild low carbon steel, and hard high carbon tool steel.

The transformer iron was investigated under three conditions. First, the apparent induction was measured with the magnetic circuit composed of the two specimens placed as close as the magnetizing coils would allow and the air gaps between the adjacent ends; that is, the specimens were not united by yokes. In the second arrangement the ends of the specimens were joined by U-shaped pieces of iron of the same material and cross section. This was an attempt to have a homogeneous magnetic circuit. In the last arrangement the specimens were connected by massive soft-iron yokes such as might ordinarily be used in the double-yoke method. The data for this experimental work on the transformer iron are shown graphically in Fig. 11, where curves I, II, and III show the results obtained without yokes, with the equisectional yokes,

TABLE XVII.

Showing how the apparent induction at a given magnetizing force decreases with the increase in the frequency of the demagnetizing current.

	High carbon steel	Low carbon steel	Soft iron with massive yokes	Soft iron with yokes of same cross section	Soft iron without yokes	Frequency
H	7.0	2.0	0.5	0.5	0.5	
B_{120}	1332	617	1134	1176	1181	120
B_{90}	1336	621	1178	1221	1229	90
B_{60}	1338	630	1207	1240	1246	60
B_{30}	1349	647	1243	1265	1270	30
B_{15}	1360	660	1266	1278	1280	15
B_{10}	1365	663	1274	1281	1283	10
B_5	1367	676	1281	1285	1286	5
B_1	1368	680	1290	1290	1290	1
B_1-B_{120}	36	63	156	114	109	
$\frac{B_1-B_{120}}{B_1}$	.03	.09	.14	.09	.08	

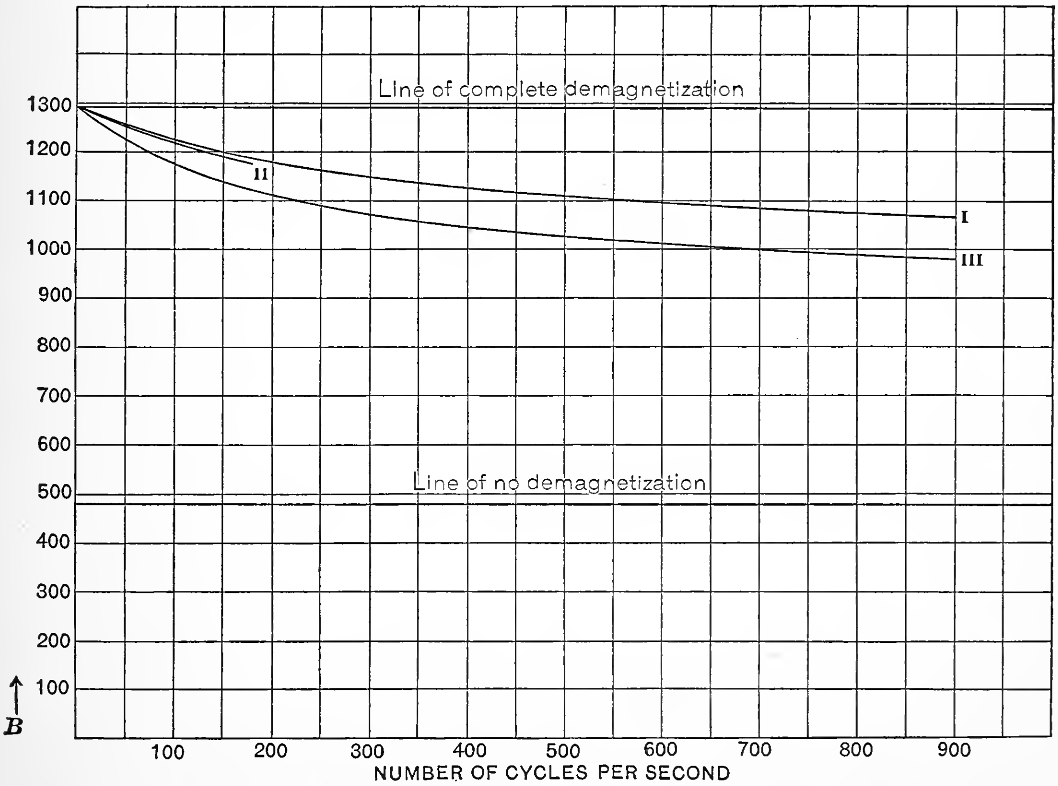

Fig. 11.—*Showing the influence of the demagnetizing frequency on the apparent induction of annealed transformer iron for $H=0.5$.*
I without yokes; II with equisectional yokes; III with massive yokes.

and with the massive yokes, respectively. Graphic representations of the data for the low and the high carbon steels are given in Figs. 12 and 13. Table XVII gives a portion of the numerical data for all three of the specimens in a form which facilitates comparison. From the graphic and numerical data given above a number of conclusions may be drawn.

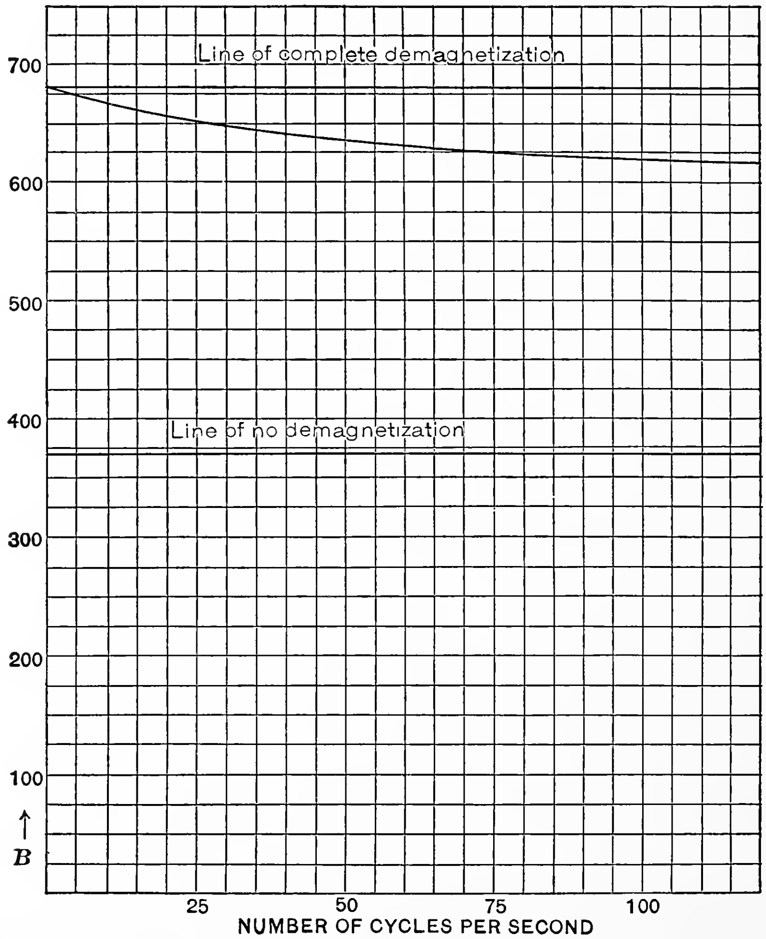

Fig. 12.—*Showing the influence of the demagnetizing frequency on the apparent induction of low carbon steel for H=2.*

(1) In every case an increase in the frequency of the demagnetizing current is accompanied by a decrease in the apparent induction as subsequently measured.

(2) In the case of the transformer iron, the polarization effect which is measured by the distance of the curve below the upper horizontal line is greater as the cross section of the yokes increases. That the polarization effect does not vanish when the yokes are

removed shows that while the yokes modify its magnitude, they are not the cause of it. In comparing the transformer iron with the other specimens the data obtained with the massive yokes should be used, as heavy yokes were used on the other specimens.

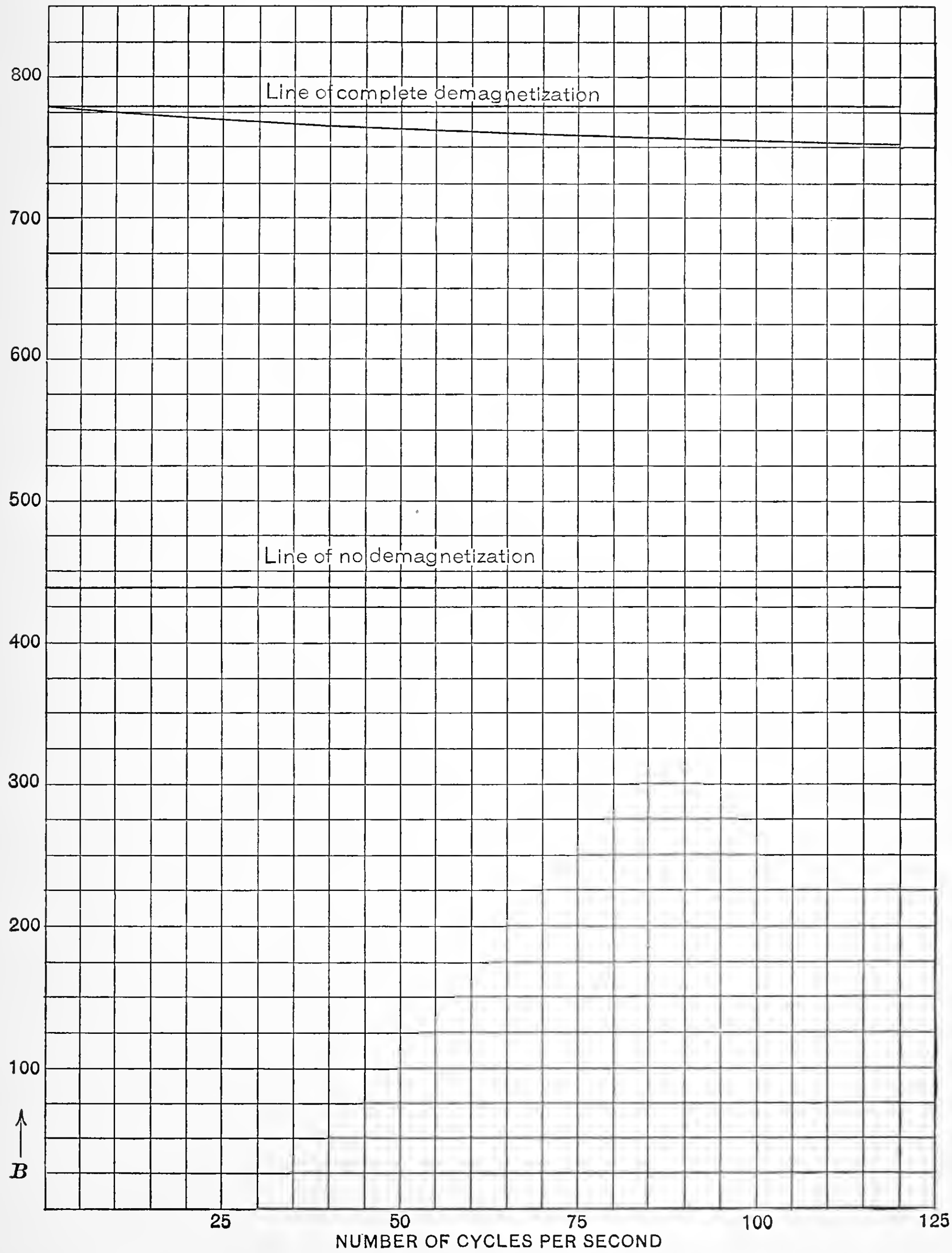

Fig. 13.—*Showing the influence of the demagnetizing frequency on the apparent induction of high carbon steel for $H=5$.*

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(3) The diminution in apparent induction—that is, the polarization effect—is relatively greater in the softer material. This statement holds also for the maximum polarization effect, as measured by the distance between the line of perfect demagnetization and the line of no demagnetization. The rate of increase of the polarization effect with the frequency of the demagnetizing current is greater in the softer materials.

TABLE XVIII.

Showing the nature of the polarization effect remaining in annealed transformer iron after demagnetizing by alternating current of 60 cycles.

Limits of demagnetizing force		*5—.2	3.5—.2	2.6—.2	No demagnetization
Time interval		77	58	34	
Number of cycles		4620	3480	2040	
H	Normal induction	Polarization effects			
.3	370	20	30	30	240
.4	670	30	30	40	440
.5	1290	50	50	70	810
.6	1680	60	60	90	960
.7	2570	80	80	100	1190
.8	3370	70	70	70	860
.9	4300	60	60	60	600
1.0	5130	50	50	50	380
1.2	6730	40	40	40	240
1.4	6950	20	20	20	90
1.6	7610	10	10	10	30
2.0	8880	0	0	0	0

* This column holds also for the following conditions:

Limits of demagnetizing force	5—.2	20—.2	36—.2	159—.2
Time interval	177	40.8	60	52
Number of cycles	4620	2448	3600	3120

NATURE OF POLARIZATION DUE TO FREQUENCY.

That the above conclusions, based on a single value of the magnetizing force, hold in general is clear from data obtained to show the nature of the polarization effect throughout the whole range of the induction curve. Table XVIII shows such a set of data for the annealed transformer iron where the results are expressed in terms of polarization effects. Several things in this table are worthy of note.

TABLE XIX.

Showing the nature of the polarization effect remaining in low carbon steel after demagnetizing by an alternating current of 60 cycles per second.

Limits of demagnetizing force		90.1—.2	42.4—.2	16.2—.2	No demagnetization
Time interval		122.8	140.6	118	
Number of cycles		7368	6436	7080	
H	Normal induction	Polarization effects			
1	190	0	12	16	100
2	680	20	50	85	310
3	1930	45	120	200	470
4	4150	100	280	420	480
5	6790	70	280	300	490
6	9140	70	200	210	370
7	9990	60	110	140	250
8	11070	50	60	90	120
9	11880	20	20	20	60
10	12470	0	0	0	10

Plotted in Fig. 14.

(1) The polarization effect exists for all values of the magnetizing force up to the critical demagnetizing force, but is much smaller than the maximum polarization effect observed after intense magnetization without subsequent demagnetization. In this respect it resembles the effect after the imperfect demagnetization due to the upper limit of the demagnetizing force being too low.

(2) The polarization effect is constant for all values of the initial demagnetizing force greater than 5. A reference to Table VIII will

show that for slow frequency the maximum demagnetizing force of 2.0 or over gave constant results. An alternating current then requires a greater initial maximum to produce its full effect.

(3) The polarization effect after a demagnetization by alternating current, even when this has a value great enough to produce its maximum effect, is of considerable magnitude and extends from the smallest values of the magnetizing force up to the critical demagnetizing force.

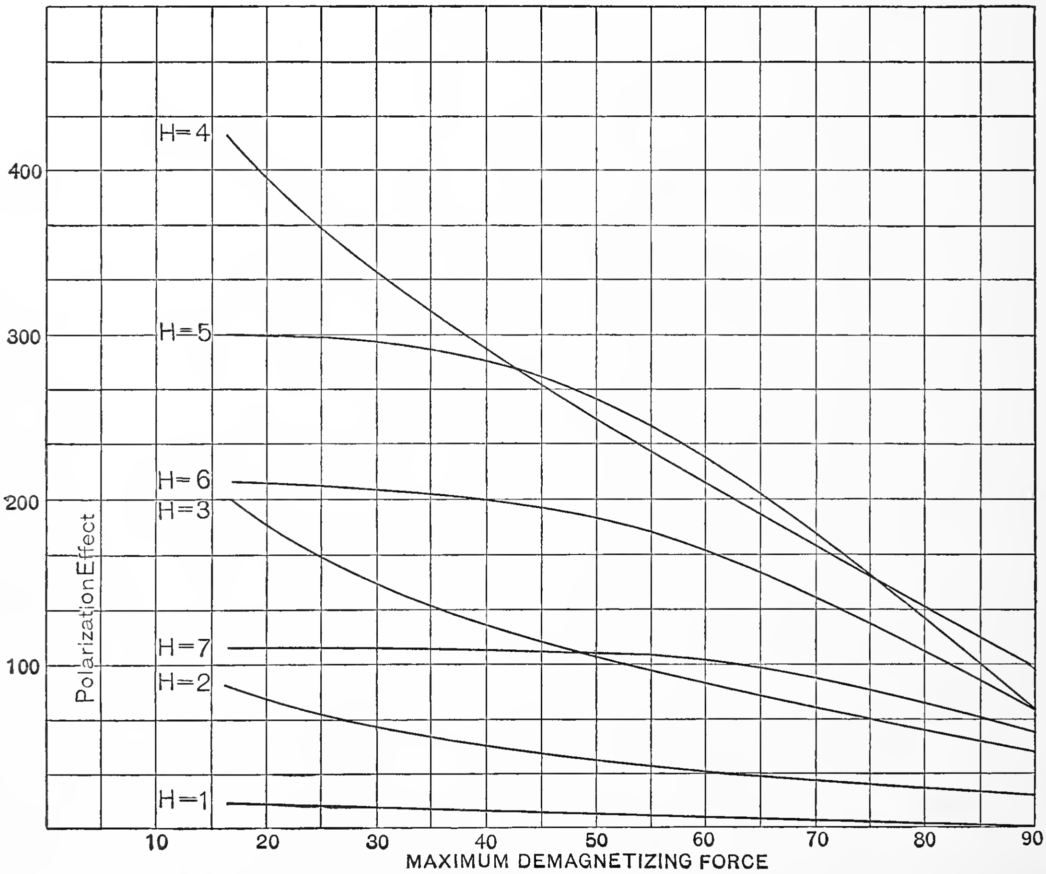

Fig. 14.—*Showing how the polarization effect in low carbon steel due to excessive frequency varies with the maximum demagnetizing force.*

(Numerical data in Table XIX.)

The low carbon steel was examined in the same way. The data for this have been shown numerically in Table XIX and graphically in Fig. 14. For this specimen also the polarization exists for all values of the magnetizing force up to the critical value. A constant value, however, was not reached at the values of the maximum demagnetizing forces used, even though a value over six times the maximum required at low frequency was used.

THE CAUSE—EDDY CURRENTS.

As was expected, the demagnetizing efficiency of an alternating current is less than that of a slowly reversed direct current. This difference is much greater in the thick round rod of low carbon steel than in the thin strip of transformer iron. (See dimensions in Table I.) Referring to Fig. 25 and assuming a mean permeability of 1000 for the round rod we see that the magnetic force on the axis is only 7 per cent of the magnetizing force exerted by the alternating current of 60 cycles. The alternating current furnished a magnetizing force of 30 units, so that in the case of the low carbon steel where the induction does not reach a constant value at the magnetizing forces used, the incompleteness is due to the combined effect of frequency and too low magnetizing current. In the case of the

TABLE XX.

Showing the influence of eddy currents during the demagnetization by alternating current on the residual polarization effect.

Limits of demagnetizing force		15—.2	5.3—.2	17.6—.2	28—.2	155—.2	28—.2
Time interval		96	57.2	72	69.8	65.6	53.8
Frequency		1.7	60	60	60	60	120
H	Normal induction	Polarization effects					
.3	370	20	70	30	30	20	40
.4	670	40	130	70	50	50	90
.5	1290	90	250	120	100	100	170
.6	1680	110	400	180	160	120	280
.7	2570	170	620	290	250	230	400
.8	3370	210	720	320	280	250	460
.9	4300	220	740	340	300	260	480
1.0	5130	240	660	350	280	240	500
1.2	6730	200	480	320	250	240	420
1.4	6950	150	350	290	200	190	320
1.6	7610	80	320	250	180	160	300
2.0	8880	30	240	180	100	100	200

Plotted in Fig. 15.

annealed iron, however, increased current does not reduce the polarization effect to zero, so that here we have an effect due solely to the frequency.

There seems no doubt that this decrease in induction after demagnetizing by alternating current is mainly an eddy current effect;

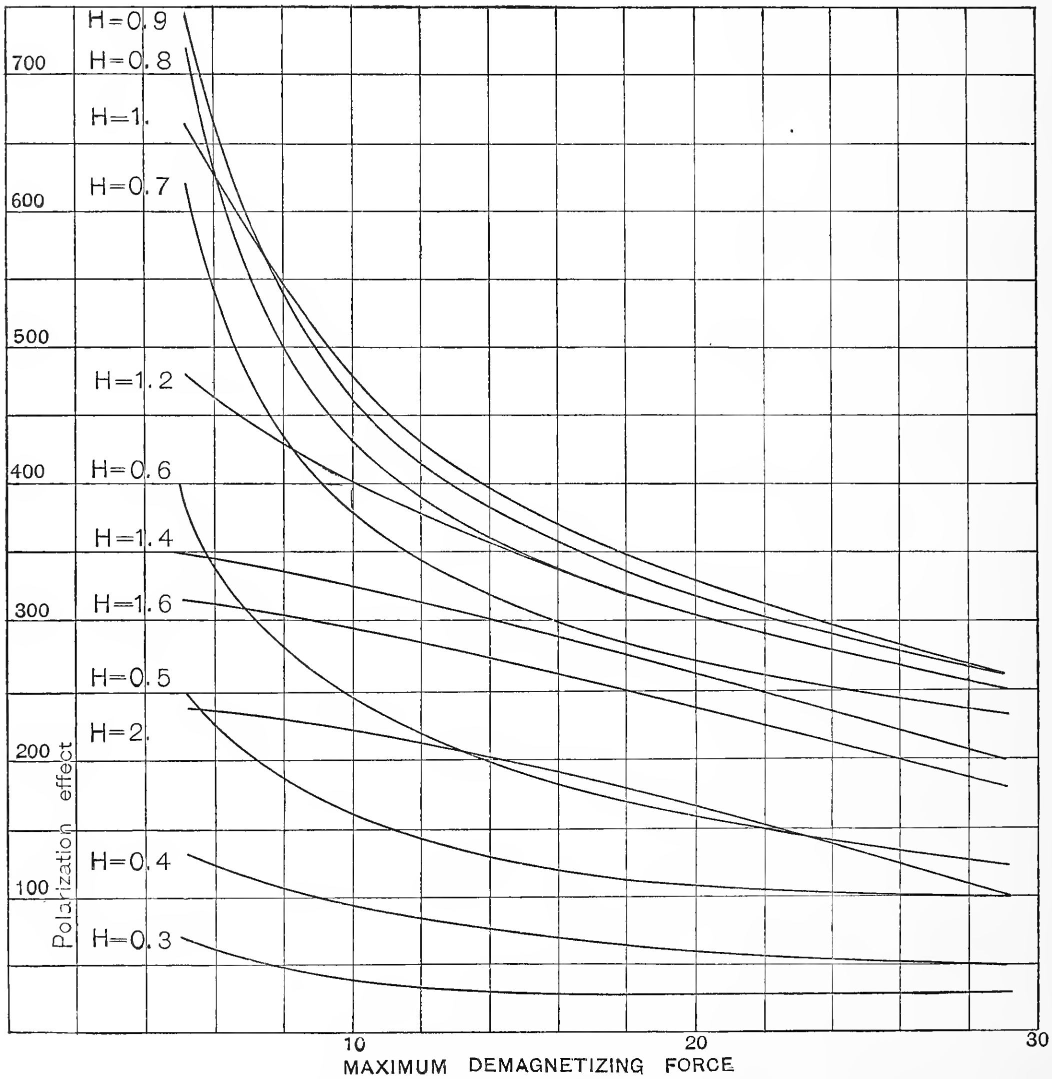

Fig. 15.—*Showing how the polarization effect in a specimen of annealed transformer iron surrounded by a copper tube, after demagnetization by an alternating current of 60 cycles, varies with the maximum demagnetizing force.*

(Numerical data in Table XX.)

nevertheless, to test this point further, one of the strips of annealed transformer iron was placed in a copper tube and the inductions measured in the regular way after various demagnetizations. The

data have been expressed as polarization effects and are recorded numerically in Table XX and graphically in Fig. 15. From the table we may draw a number of conclusions.

(1) The polarization effect even after slow reversals is not zero as we should expect it to be for perfect demagnetization.

(2) The polarization after a maximum demagnetizing force of 5 is much greater than it was when the copper tube was off. As the maximum force increases the polarization effect decreases throughout the whole range of magnetizing forces in much the same way as it does when the polarization effect is decreased by carrying the upper limit of a slowly reversed demagnetizing force up nearer and nearer to the critical value. The sixth and eighth columns of this table show that doubling the demagnetizing frequency, other conditions remaining unaltered, approximately doubles the polarization effect.

(3) The curves of Figs. 14 and 15 were drawn primarily to show how the polarization effect decreases as the upper limit of the demagnetizing force increases. The form of these curves is interesting. For the lower values of H these curves are concave upward. As the value of H increases the initial curvature increases, reaches a maximum in the neighborhood of the maximum of the permeability, finally decreases and becomes convex upward for the higher values of H. Other data seem to indicate that all of these curves become concave upward for large values of the upper limit of the demagnetizing force.

CONSTANCY OF RESULTS.

Another and very important fact brought out during the course of these experiments is the uniform consistency with which results are reproduced. Thus, while an alternating current of a frequency of 90 cycles per second will give a residual polarization effect it always gives the same residual value, and the induction curve obtained after such demagnetization may be repeated any number of times. No evidence of imperfect demagnetization exists except the fact that higher inductions may be obtained under other methods of demagnetization. This probably accounts for the fact that so many experimenters consider an alternating current demagnetization as entirely satisfactory. Furthermore, the polarization effect remain-

ing after demagnetization by alternating current decreases with decrease in the thickness of the specimen so that in the case of the thin transformer iron, such as that used in this investigation (.036 cm), or in the work of Professor Searle (.034 cm and .037 cm), the error introduced by imperfect demagnetization is negligible except in the steep part of the *B–H* curve. It is in the case of specimens of large cross section that the objections to alternating current demagnetization have most weight.

TABLE XXI.

Showing the nature of the residual polarization effect in annealed transformer iron caused by the time interval of demagnetization being too brief.

Limits of demagnetizing force		15—.2	15—.2	15—.2	No demagnetization
Time interval		74 or over	58	20	
Number of cycles		110 or over	85	27	
H	Normal induction	Polarization effects			
.3	370	0	10	30	240
.4	670	0	20	70	440
.5	1290	0	20	80	810
.6	1680	0	30	100	960
.7	2570	0	50	150	1190
.8	3370	0	40	120	860
.9	4300	0	40	110	600
1.0	5130	0	20	60	380
1.2	6730	0	0	40	240
1.4	6950	0	0	0	90
1.6	7610	0	0	0	30
2.0	8880	0	0	0	0

As a general conclusion from the preceding, it is evident that the best demagnetization is obtained with the slowest reversals. As, however, the curves of Figs. 11, 12, and 13 cut the vertical axis at a value of the induction not far different from the value at a demagnetizing frequency of one cycle per second, we may without sensi-

ble difference and with great economy of time use a frequency of one cycle per second in practice. The fact that the constant value of the apparent induction after the best demagnetization which a 60-cycle current can give is less than the normal induction indicates that something else besides eddy currents is reducing the value of the induction. This something is probably closely related to the phenomenon of magnetic viscosity.

TIME INTERVAL OF DEMAGNETIZATION.

Having determined the proper frequency and limits for the demagnetizing force it now remains to determine the effect of variations in the time interval of demagnetization. With this in view the iron

TABLE XXII.

Showing the nature of the residual polarization effect in common sheet iron caused by the time interval of demagnetization being too brief.

Limits of demagnetizing force		15—.2	15—.2	15—.2	15.—2	No demagnetization
Time interval		58.2 or over	33.6	18	7	
Number of cycles		82 or over	53	25	11	
H	Normal induction	Polarization effects				
1	263	0	15	18	28	166
2	1314	0	26	94	124	818
3	3770	0	50	105	130	640
5	7890	0	25	35	60	160
7	10270	0	0	10	20	140
10	12170	0	0	0	0	10
15	13160	0	0	0	0	0

was demagnetized at a slow rate of reversal and between the demagnetizing limits determined upon above. This was done a number of times, varying the time interval of demagnetization; that is, the number of cycles. The numerical results for transformer iron, common sheet iron, and low carbon steel are given in Tables XXI, XXII, and XXIII. From these data it appears that the polarization effect

is zero for all values of the magnetizing force, provided the demagnetization has taken approximately a minute. If the time is too brief the polarization effect extends over nearly the whole range from the lowest values up to that of the critical demagnetizing force. It increases in magnitude as the time decreases. Too brief a time interval has the same effect as too small a current or too high a

TABLE XXIII.

Showing the nature of the residual polarization effect in low carbon steel caused by the time interval of demagnetization being too brief.

Limits of demagnetizing force		15—.2	15—.2	No demagnetization
Time interval		75 or over	67	
Number of cycles		83 or over	100	
H	Normal induction	Polarization effects		
1	190	0	0	100
2	680	0	5	310
3	1930	0	20	470
4	4150	0	25	480
5	6790	0	40	490
6	9140	0	25	370
7	9990	0	20	250
8	11070	0	0	120
9	11880	0	0	60
10	12470	0	0	10
15	14170	0	0	0

frequency. A comparison of the polarization effect after no demagnetization with that after the briefest interval shows that the greater portion of the polarization effect is wiped out by the first few reversals.

Table XXIV shows the effects of variations in the time interval when the demagnetization is carried on at a somewhat higher frequency. The full effect of the demagnetization while less than before is reached in a shorter interval of time and therefore seems to depend on the number of cycles rather than the time. From this it is

TABLE XXIV.

Showing how the time interval of demagnetization influences the apparent induction.

Demagnetizing frequency=14		
Time interval	Number of cycles	Apparent induction
Annealed transformer iron for H=.5		
No demagnetization		480
10	140	1225
14	196	1240
25	350	1265
26	364	1265
47	658	1265
130	1352	1265
273	3822	1265
310	4340	1265
Normal		1290
Low carbon steel for H=2		
No demagnetization		370
2.4	34	640
3.2	45	649
4.2	59	660
4.6	64	661
7.4	104	662
18.0	252	662
44.0	616	662
Normal		680
High carbon steel for H=10		
No demagnetization		2600
26	364	2960
53	742	2960
126	1764	2960
221	3094	2960
Normal		2980

evident that if the time of demagnetization is kept constant while the frequency is varied, there will be a tendency for the induction to increase as the frequency decreases as long as the time interval is great enough to allow the demagnetizing current to accomplish

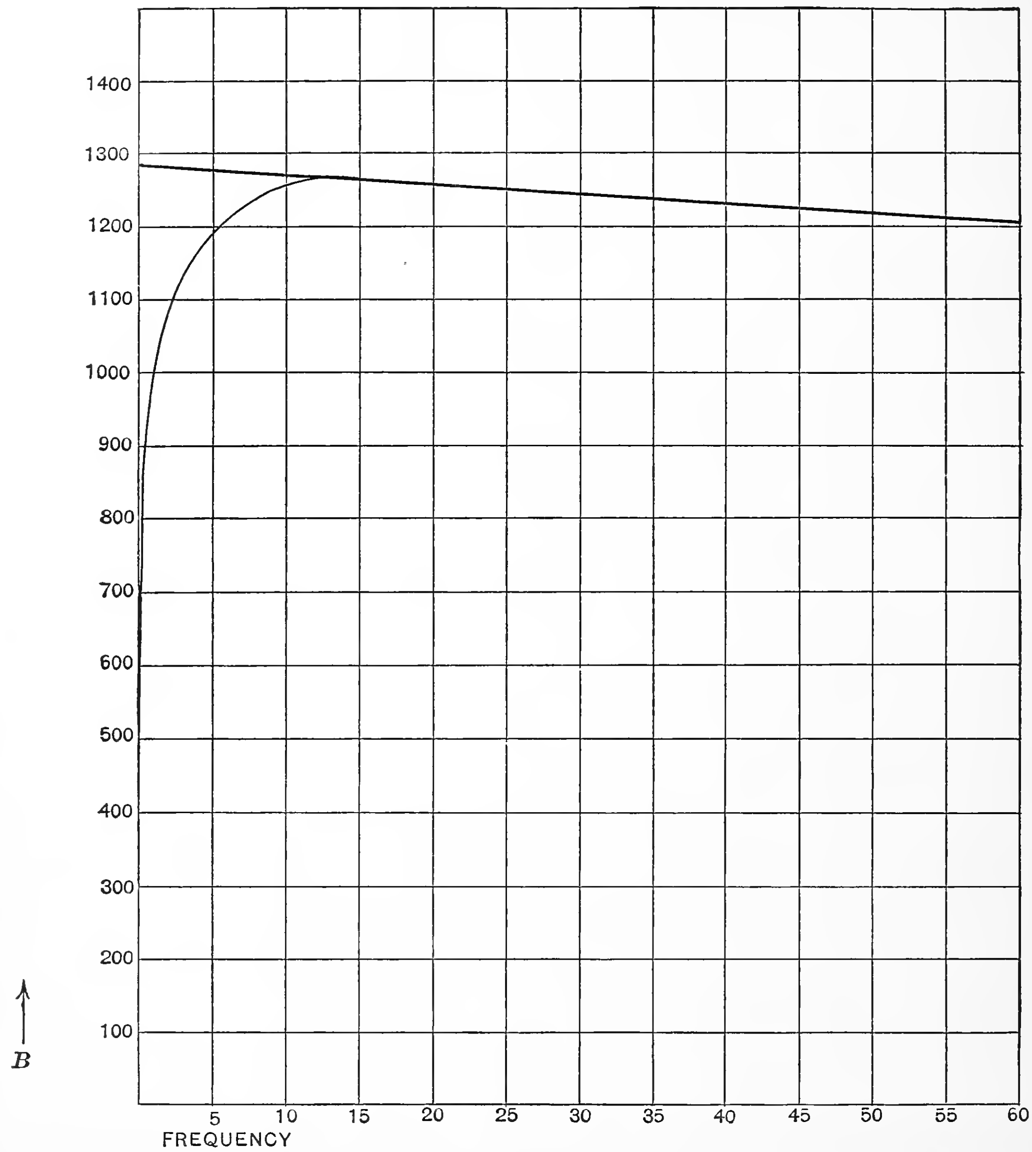

Fig. 16.—*Showing the combined effect of frequency and time interval of demagnetization on the apparent induction of transformer iron when $H=0.5$.*

its full effect. For the lower frequencies, though a greater efficiency is possible, a longer time is required, and if this is too short the effect of the briefness may exceed the advantage due to the slower frequency and the induction diminishes from a certain point on as

the frequency decreases. This is exactly what happened in one of the earlier experiments of this investigation. A portion of the data obtained is shown graphically in Fig. 16. This curve led to the erroneous conclusion that a frequency of fourteen cycles per second was the best frequency for the demagnetizing current.

THE NORMAL INDUCTION.

After the iron has been thus freed from all traces of previous magnetic polarization it is ready for the ballistic determination.

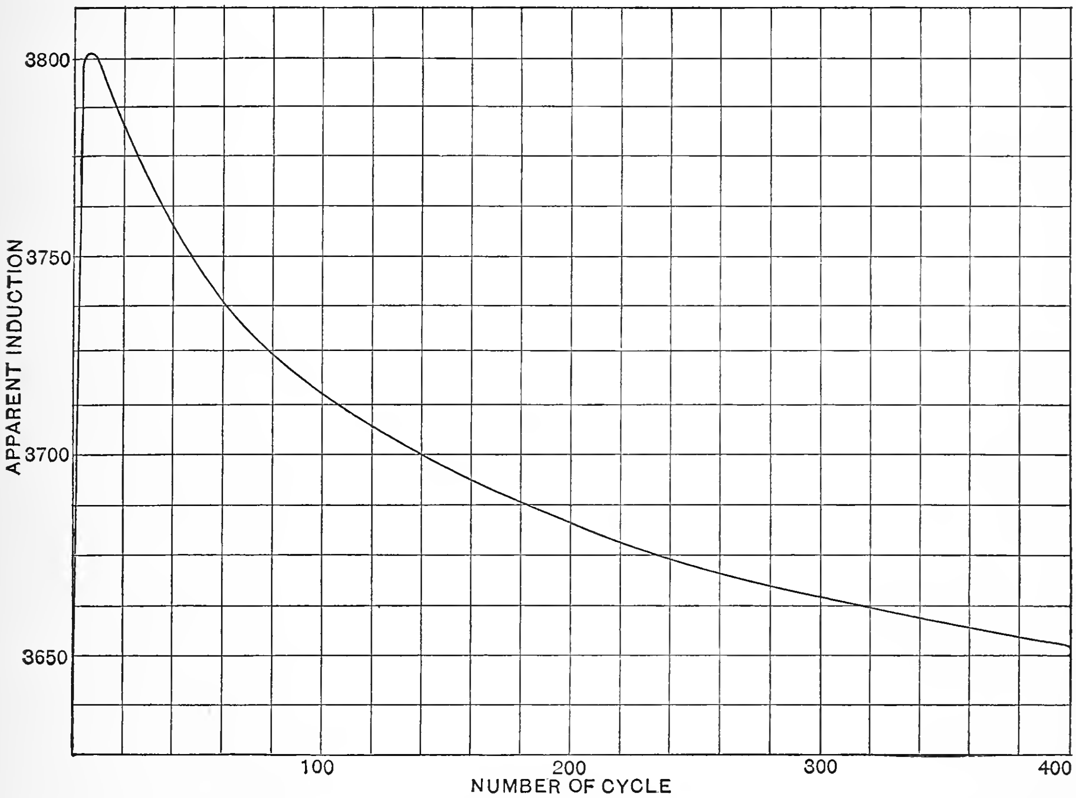

Fig. 17.—*Showing the manner in which the apparent induction of an iron ring changes on successive reversals of the magnetizing force.*

We have earlier defined true induction as the normal cyclic induction. The reason for this is apparent from the following:

The induction at the point of maximum differential permeability in a bundle of ring stampings of thin annealed transformer iron was determined for successive reversals of the magnetizing force. The results appear in Fig. 17, where the number of the cycle is plotted on the horizontal axis and inductions along the vertical. The ver-

tical scale is greatly enlarged so as to show the characteristics of the curve. This curve shows three characteristic parts. The first few reversals show a rapidly increasing apparent induction, then a maximum value is passed, and finally the apparent induction decreases, at first quite rapidly, then more and more gradually, and finally approaches a lower limit asymptotically. As the test specimen in this case is an endless ring with the magnetizing coil wound

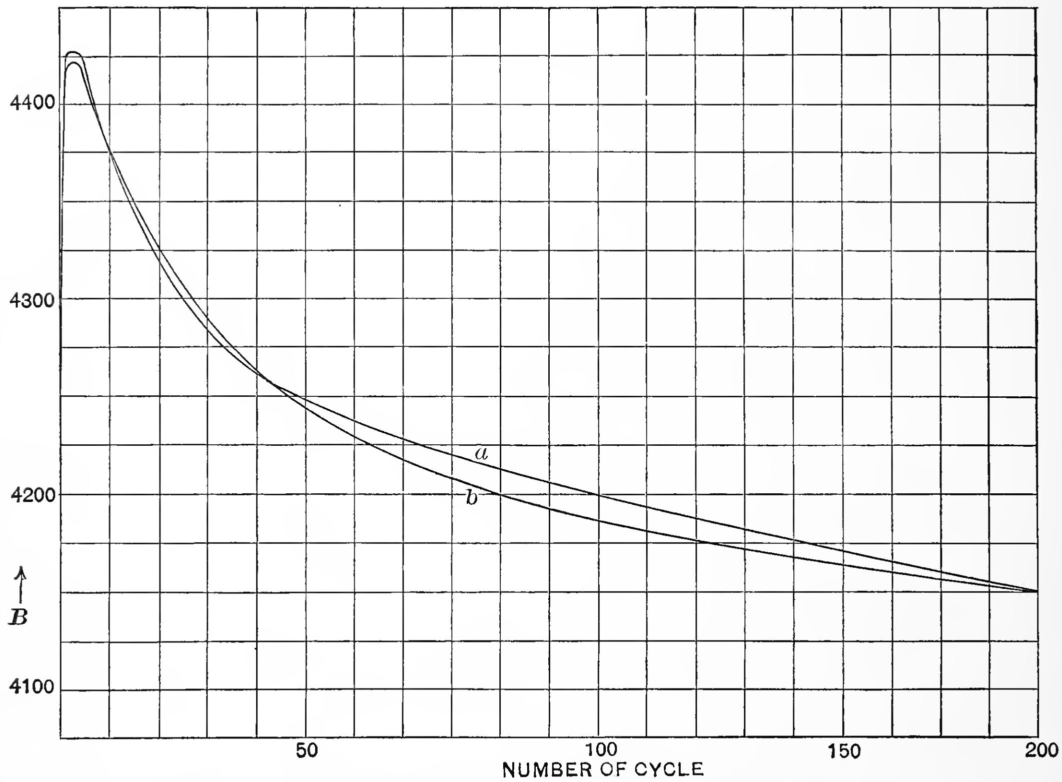

Fig. 18.—*Showing the manner in which the apparent induction of low carbon steel changes with successive reversals of the force $H=4$.*
(a) with yokes, and (b) without yokes.

uniformly this phenomenon can not be due to any end effect. Similar curves taken with straight rods of low carbon steel are shown in Fig. 18. The curve "a" represents data in which the rods were joined together by yokes, while for curve "b" the rods were not joined but placed as close as the magnetizing coils would allow. These two curves have the same characteristics as the one obtained from the ring. They are so nearly alike that no modifying effect can be attributed to the yokes. To examine more fully the manner in which the cyclic state is reached for various values

of the magnetizing force, complete induction curves were obtained for several values of the magnetizing force after certain numbers of reversals. This was done for annealed transformer iron, low carbon steel, and high carbon steel, and the data are given in Tables XXV, XXVI, and XXVII, and in part are shown graphically in figures 19, 20, and 21. Both from the curves and the summaries at the bottom

TABLE XXV.

Showing the manner in which completely demagnetized transformer iron approaches the cyclic state.

Number of cycle	Apparent induction						
	H=.5	H=1	H=2	H=3	H=5	H=10	H=15
1	1300	5350	9100	10850	12800	14620	15280
2	1325	5400	9200	11000	12810	14630	15290
3	1320	5440	9210	11020	12800	14630	15280
4	1320	5470	9200	11020	12780	14630	15280
5	1320	5490	9190	11010	12770	14620	15280
20	1318	5400	9100	10950	12750	14620	15280
50	1310	5300	9030	10880	12750	14620	15280
100	1302	5215	8970	10810	12750	14620	15280
200	1294	5150	8915	10760	12750	14620	15280
400	1292	5140	8890	10760	12750	14620	15280
600	1290	5130	8880	10750	12750	14620	15280
B_{max}	1325	5490	9210	11020	12810	14630	15290
B_{final}	1290	5130	8880	10750	12750	14620	15280
$B_{max}-B_{final}$	35	360	330	270	60	10	10
$\frac{B_{max}-B_{final}}{B_{final}}$	.03	.07	.04	.03	.00	.00	.00

Plotted in Fig. 19.

of the tabulated data it is evident that the difference between the maximum apparent induction and its final value increases in all the specimens as the value of H used approaches that of maximum permeability. This difference in apparent inductions divided by the final apparent induction gives a quotient which is a maximum at approximately the point where the differential permeability is a

maximum. No marked difference in the manner in which the various specimens approach the cyclic state can be noticed. Any irregularities that occur in the curve indicating the manner of approach are found during the first few cycles, and are due probably to a

TABLE XXVI.

Showing the manner in which low carbon steel approaches the cyclic state after one initial demagnetization.

Number of cycle	Apparent induction						
	$H=1$	$H=3$	$H=4.$	$H=5$	$H=7$	$H=10$	$H=15$
1	191	1920	4210	6860	10060	12450	14170
2	192	1930	4240	6890	10070	12510	14180
3	192	1940	4270	6920	10070	12500	14180
4	192	1960	4280	6920	10060	12500	14180
5	192	1970	4290	6925	10060	12490	14180
6	191	1980	4290	6930	10060	12490	14170
7	191	1990	4290	6930	10050	12490	14170
8	190	1990	4290	6930	10050	12480	14170
9	190	1985	4280	6930	10050	12480	14170
10	190	1985	4280	6925	10050	12470	14170
20	190	1980	4260	6905	10040	12470	14170
50	190	1970	4250	6880	10030	12470	14170
100	190	1960	4220	6850	10020	12470	14170
200	190	1950	4190	6810	10010	12470	14170
400	190	1940	4160	6800	9990	12470	14170
600	190	1930	4150	6790	9990	12470	14170
B_{max}	192	1990	4290	6930	10070	12510	14180
B_{final}	190	1930	4150	6790	9990	12470	14170
$B_{max}-B_{final}$	2	60	140	140	80	40	10
$\frac{B_{max}-B_{final}}{B_{final}}$	.01	.03	.03	.02	.01	.00	.00

Plotted in Fig. 20.

small residual polarization which is large enough to modify the first reversal but is soon wiped out by continued reversals. Such irregularities might be expected in accordance with the theory of molecular magnets. In view of the preceding experiments it seems quite proper

to fix upon the final minimum value of the apparent induction as the *definition* of the true normal induction. The initial and maximum values are rejected because of their uncertainty and the fact that they can not be verified by repetition without another demag-

TABLE XXVII.

Showing the manner in which demagnetized high carbon steel approaches the cyclic state under various forces.

Number of cycle	Apparent induction					
	$H=1$	$H=2$	$H=5$	$H=10$	$H=15$	$H=40$
1	109	254	790	3130	6780	11660
2	109	254	795	3160	6790	11670
3	109	254	796	3190	6800	11670
4	109	254	795	3190	6805	11680
5	108	254	790	3190	6800	11680
6	108	252	785	3170	6800	11680
7	108	252	785	3150	6800	11670
8	108	250	780	3140	6800	11670
10	108	249	780	3140	6800	11670
20	108	249	780	3130	6790	11670
50	108	249	780	3100	6760	11670
100	108	249	780	3050	6730	11670
200	108	249	780	3020	6700	11670
400	108	249	780	2990	6690	11670
600	108	249	780	2980	6680	11670
800	108	249	780	2980	6680	11670
B_{max}	109	254	796	3190	6805	11680
B_{final}	108	249	780	2980	6680	11670
$B_{max}-B_{final}$	1	5	16	210	125	10
$\frac{B_{max}-B_{final}}{B_{final}}$	.01	.02	.02	.07	.02	.00

Plotted on Fig. 21.

netization. These reasons apply whether the induction is to be measured ballistically or magnetometrically, and if results are to be compared by these two methods care must be taken that the inductions have been measured under the same conditions.

ONE DEMAGNETIZATION SUFFICIENT.

It has been suggested by Searle that the specimen should be demagnetized before each determination of an induction. We have already shown that after demagnetization the cyclic induction at

TABLE XXVIII.

Showing the manner in which low carbon steel approaches a cyclic state under various forces, when it has been demagnetized before each new force is applied.

Number of cycle	Apparent induction					
	$H=1$	$H=3$	$H=4$	$H=5$	$H=7$	$H=10$
Make	190	1900	4200	6800	9980	12460
1	191	1920	4250	6890	10000	12500
2	191	1910	4260	6890	10010	12500
3	191	1920	4270	6900	10040	12510
4	192	1950	4290	6900	10080	12510
5	192	1970	4290	6910	10080	12520
6	191	2000	4300	6920	10060	12520
7	190	2010	4300	6920	10060	12510
8	190	2010	4290	6930	10060	12510
9	190	2000	4290	6930	10050	12510
10	190	2000	4280	6930	10050	12500
20	190	1990	4260	6910	10040	12470
50	190	1980	4250	6890	10030	12470
100	190	1960	4230	6850	10020	12470
200	190	1950	4190	6810	10010	12470
400	190	1940	4160	6800	10000	12470
600	190	1930	4150	6790	9990	12470
B_{max}	192	2010	4300	6930	10080	12520
B_{final}	190	1930	4150	6790	9990	12470
$B_{max}-B_{final}$	2	80	150	140	90	50
$\frac{B_{max}-B_{final}}{B_{final}}$	.01	.04	.04	.02	.01	.00

any magnetizing force is not affected by any preceding application of smaller forces; but as this is an important detail of manipulation it is desirable to leave no uncertainty. Two sets of data were there-

fore obtained—one for a single demagnetization and another in which the specimen was demagnetized before each measurement of the induction. The two sets of data are given in the Tables XXVI and XXVIII.

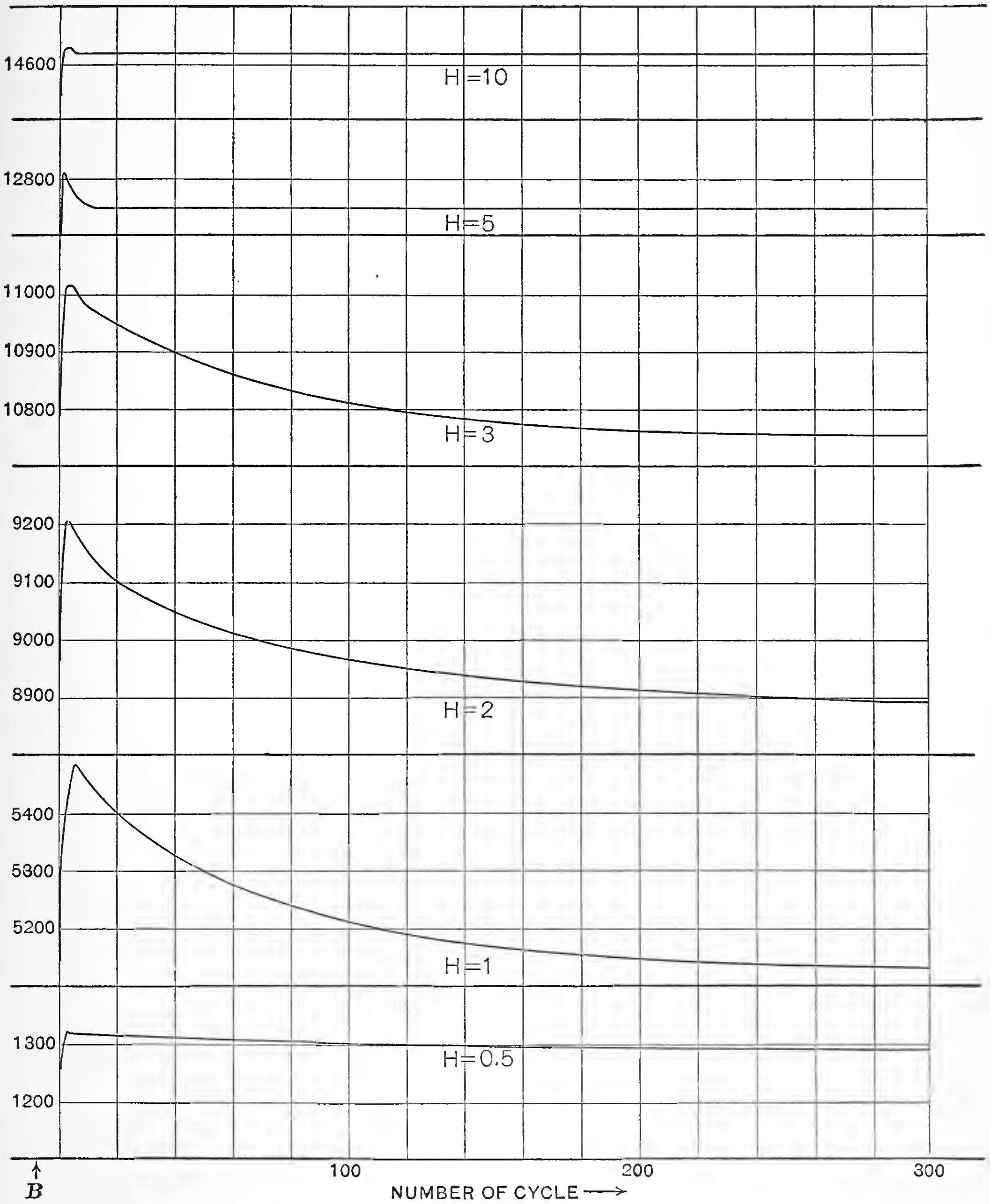

Fig. 19.—*Showing the manner in which demagnetized transformer iron approaches the cyclic state for various values of H.*

(Numerical data in Table XXV.)

The final values of the induction are the same in each case, and the main characteristics of the manner of approach to the cyclic state

are maintained in each. Whatever differences there are occur in the earlier reversals. This is another argument in favor of the final value as the normal one.

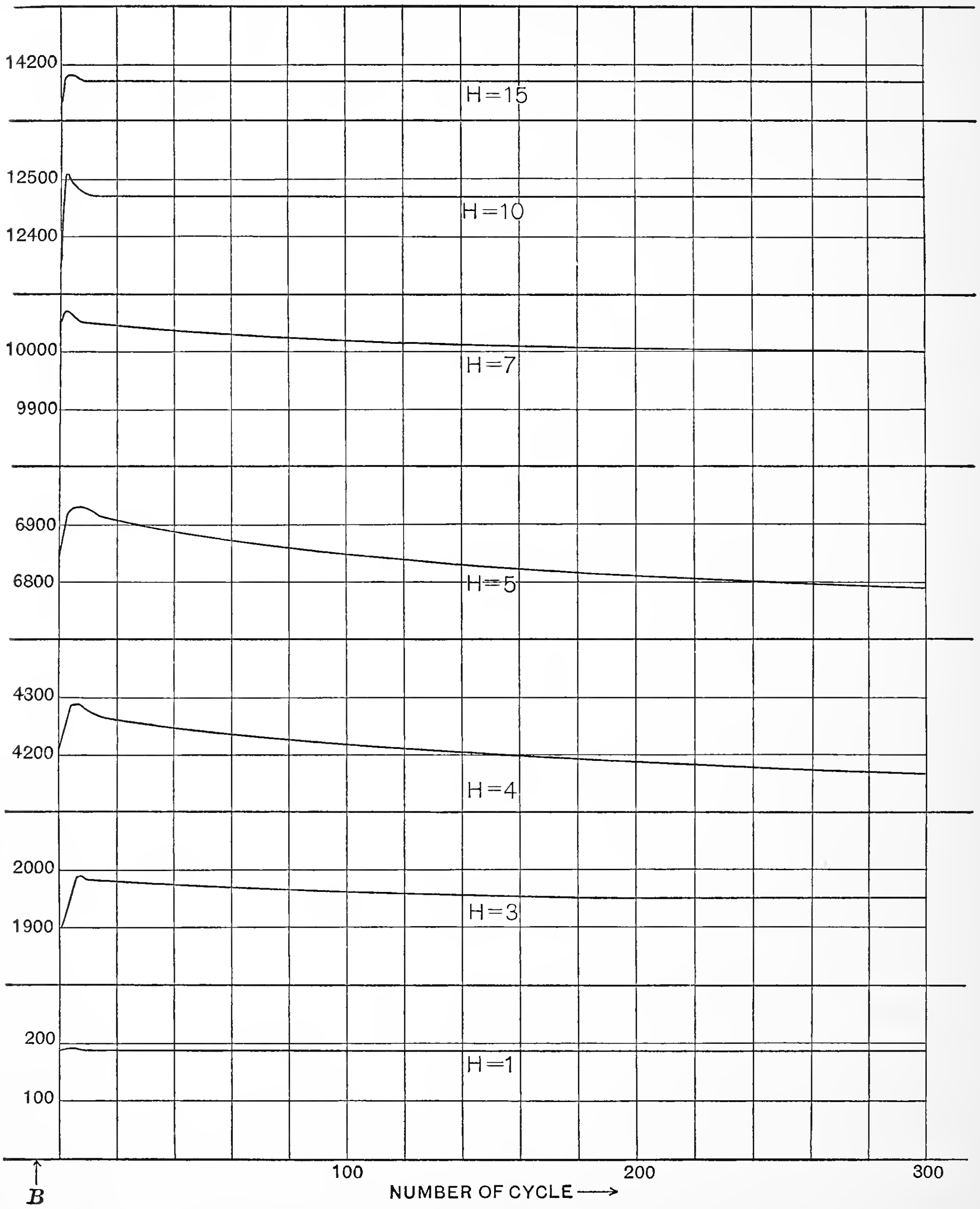

Fig. 20.—*Showing the manner in which demagnetized low carbon steel approaches the cyclic state for various values of H.*

(Numerical data in Table XXVI.)

EFFECT OF VISCOSITY.

Fig. 22 shows the manner of approach to the cyclic state under two circumstances. The upper curve shows how a specimen of

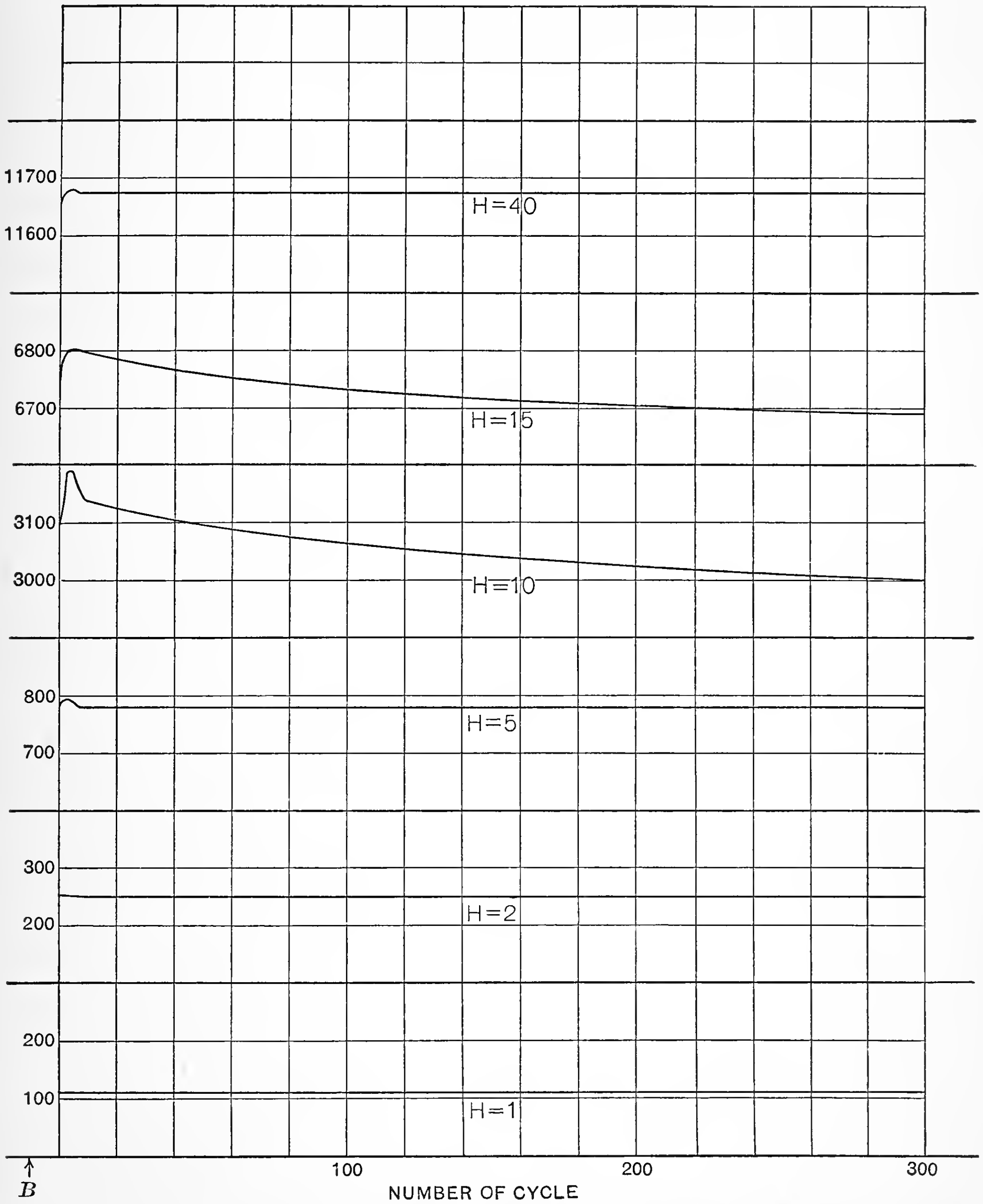

Fig. 21.—*Showing the manner in which demagnetized high carbon steel approaches the cyclic state for various values of H.*

(Numerical data in Table XXVII.)

high carbon steel comes to a cyclic state on repeated reversals of the magnetizing force by hand switch. The solid portion of the curve

just below this shows apparent inductions as actually observed after imperfect demagnetization. Between the solid portions of this curve reversals were made quite rapidly—several times per second. The dash lines give the hypothetical curve the apparent induction would have followed if the apparent induction had been measured for each reversal and no rapid reversals had been made. There are two causes of irregularities in the curve showing the manner of approach

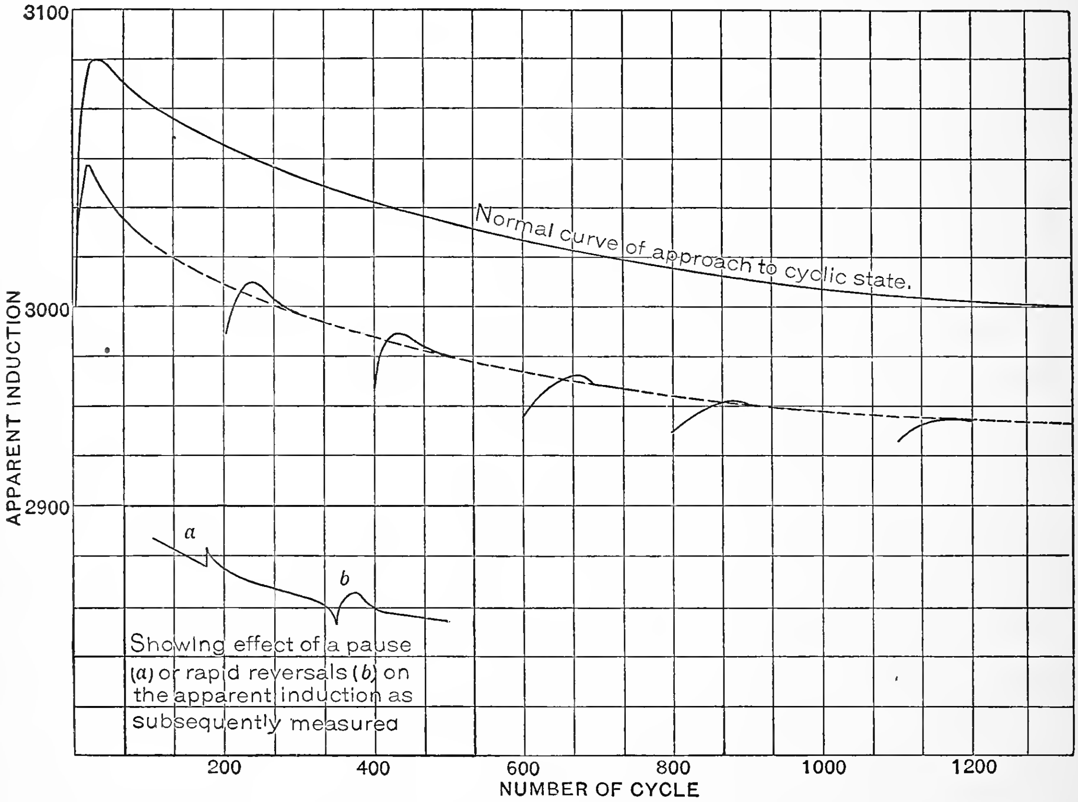

Fig. 22.—*Showing how the manner of approach to the cyclic state in high carbon steel is modified by rapid reversals of the magnetizing force and by long pauses.*

to the cyclic state. A pause at any point in the curve causes the apparent induction of the succeeding reversal to be a little larger than the one immediately preceding. This is most pronounced in the softer materials and for any specimen is greatest in the steep part of the induction curve and disappears almost completely in the upper parts of this curve. It is noticeable even after the iron has reached a cyclic state under normal conditions. The phenomenon may be attributed to magnetic viscosity. The connection is made clear from the following figure. (Fig. 23). Suppose the iron

has been subjected to forces of $+H$ and $-H$ alternately at the rate of one reversal per second. Then it will trace a hysteresis loop having its vertices at two symmetrical points as A and B. If, however, the reversals are interrupted when the iron is at the point A, the steady application of the force will cause the induction to creep from A to A′. After this creeping has ceased a reversal of the magnetizing force will bring the state point down to B. A further pause will again show a creeping from B down to B′, which is symmetric with A′. A magnetometric measurement would take account of this creeping and would measure the induction Oa′. A ballistic measurement however would indicate only the portion Oa, the remainder aa′ being lost on account of its slowness. This is on the assumption that a ballistic galvanometer with sufficient torsion in its suspension to bring its movable system back to zero is used. An instrument whose movable system has no directive force, such as the Grassot fluxmeter, would measure the full induction as completely as the magnetometer. However, even with an ordinary ballistic galvanometer this full induction can be determined. Let a ballistic deflection be taken when the iron is traversing the cycle AB. This will be proportional to ba. After a pause take the deflection on the return reversal. This will be proportional to a′b. The second deflection exceeds the first by aa′, which is the amount of creeping at one end of the cycle. The full induction would therefore be proportional to ba+2aa′. As this creeping is greatest in the steep part of the B–H curve a single determination here will tell whether it is of sufficient magnitude to warrant consideration. In some of the irons measured it has amounted to as much as 1 per cent.

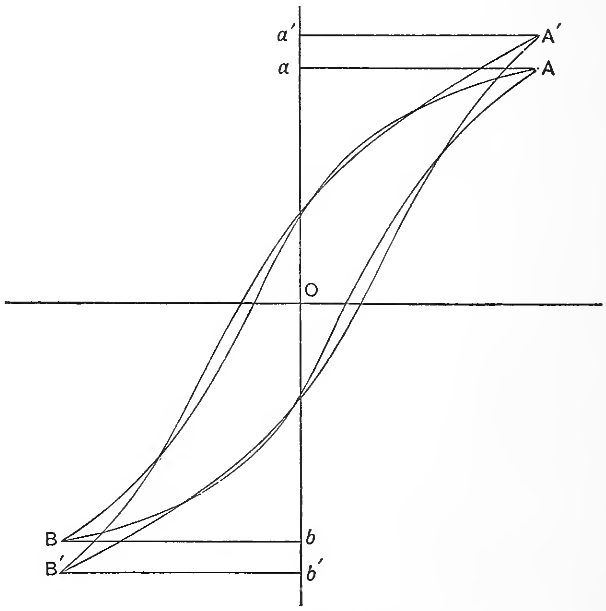

Fig. 23.—*Ideal curve to illustrate the effect of magnetic viscosity on the apparent induction.*

Another irregularity in the curve showing the manner of approach to the cyclic state is the peculiar effect of several rapid reversals. After such treatment the first inductions are too low, then the succeeding ones are too high, but after some slow reversals the inductions show no sign of irregularity. The two kinds of irregularity are shown graphically in the lower corner of Fig. 22.

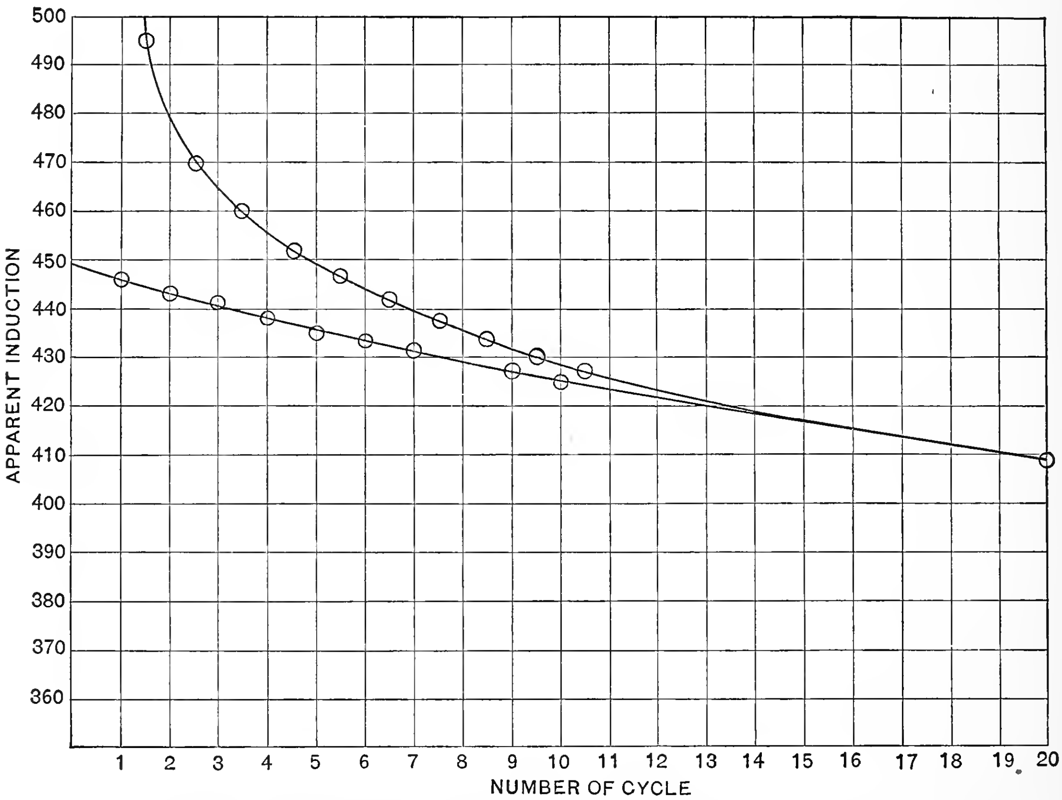

Fig. 24.—*Showing the manner in which a highly polarized bar of low carbon steel approaches the cyclic state on repeated reversals of a force $H=2$.*

(Numerical data in Table XXIX.)

EFFECT OF REPETITION.

One might suppose that a sufficient number of reversals of the magnetizing force would obviate the necessity of demagnetization. This is not the case, however, as is seen from the manner in which a specimen of low carbon steel approaches the cyclic state after intense polarization by a force of 100. The data for this experiment are shown numerically in Table XXIX and graphically in Fig. 24. The inductions on successive reversals do not form a smooth curve as those obtained after complete demagnetization would, but

those inductions obtained by reversing the magnetizing force from the direction in which the strong polarization was applied are greater than those due to either the preceding or the following reversals in the opposite direction. Thus Fig. 24 shows two lines, converging after about twenty reversals. As the reversals continue the apparent induction becomes gradually smaller, differing

TABLE XXIX.

Showing the manner in which a highly polarized piece of low carbon steel approaches the cyclic state.

Polarizing force, 100; Cyclic force, 2

Number of cycle	Apparent induction		Number of cycle	Apparent induction	
½ (make)	2500		7 ½	438	
1 (reverse)		446	8		429
1 ½ (reverse)	495		8 ½	437	
2		443	9		427
2 ½	470		9 ½	430	
3		441	10		425
3 ½	460		10 ½	427	
4		438	20		409
4 ½	452		20 ½	409	
5		435	50		388
5 ½	447		100		376
6		433	200		370
6 ½	442		1200		370
7		431	Normal induction		680

Plotted on Fig. 24.

more and more from the normal induction. After 200 cycles (400 reversals) the apparent induction has reached a minimum which a thousand double reversals do not alter. In another case a bar of polarized iron was subjected to slow reversals of the magnetizing force for four hours and yet showed no increase in the apparent induction.

STRONG VIBRATIONS.

While the study of magnetism was yet in its infancy Gilbert discovered that a soft iron bar could be quite strongly magnetized by

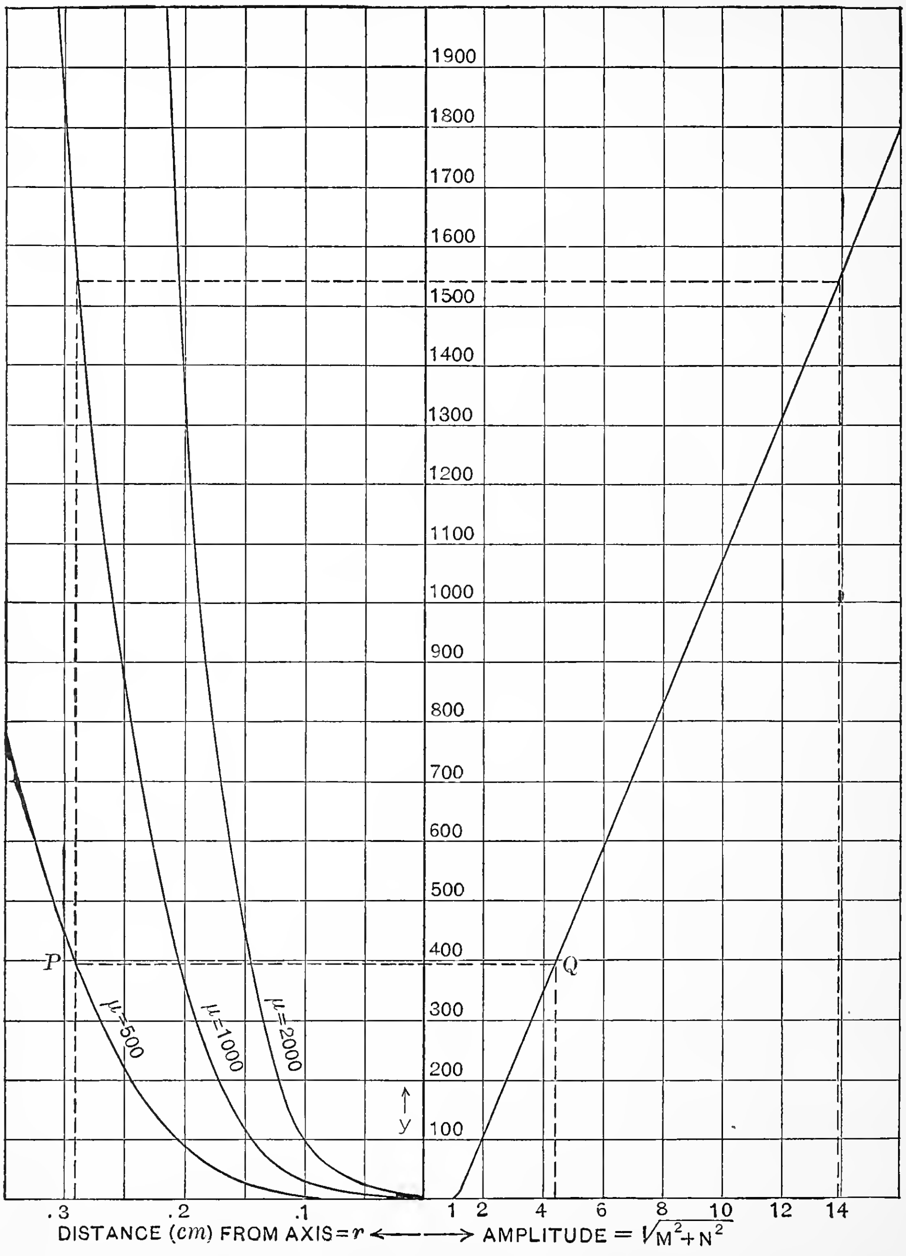

Fig. 25.—*Theoretical curves based on Heavisides's formula showing how the amplitude of an alternating magnetic flux varies over the cross section of a round rod for various assumed values of the permeability.*

holding it in the earth's field and striking it a sharp blow with a hammer. A soft iron wire placed in the terrestrial field and gently

rubbed takes up a magnetization far greater than its permeability determined in the usual way would indicate. Equally gentle rubbing will remove the major portion of the most intense residual magnetization. Ewing[18] has investigated quite thoroughly the effect of intense mechanical disturbances on the magnetic state of a bar of

TABLE XXX.

Showing the increase of induction in soft iron due to very gentle vibration.

H	B Normal	B With tapping	Increase of B due to tapping	Per cent increase of B
.2	200	211	11	5
.3	370	395	25	7
.4	600	645	45	7
.5	950	1018	68	7
.6	1445	1542	97	7
.7	2400	2525	125	5
.8	3400	3535	135	4
.9	4200	4340	140	3
1.0	4850	4985	135	3
1.1	5400	5525	125	2
1.2	5900	6010	110	2
1.3	6350	6440	90	1
1.4	6700	6770	70	1
1.5	7050	7100	50	1
1.6	7350	7380	30	0
1.7	7600	7620	20	0
1.8	7850	7860	10	0
1.9	8100	8105	5	0
2.0	8300	8300	0	0

Plotted on Fig. 26.

iron. The effect of vibration is to shake in more induction if the magnetic force is acting, and to shake out the residual induction if no magnetic force is acting. The hysteresis loop is contracted and draws in close to the induction curve, which loses its point of inflection and apparently starts out with a maximum permeability which

[18] Magnetic Induction, etc., pp. 77 and 84.

steadily decreases. While the increase in permeability is appreciable in moderately strong fields, it is in weak fields that the effect is most striking. In the case recorded by Ewing and which we have no

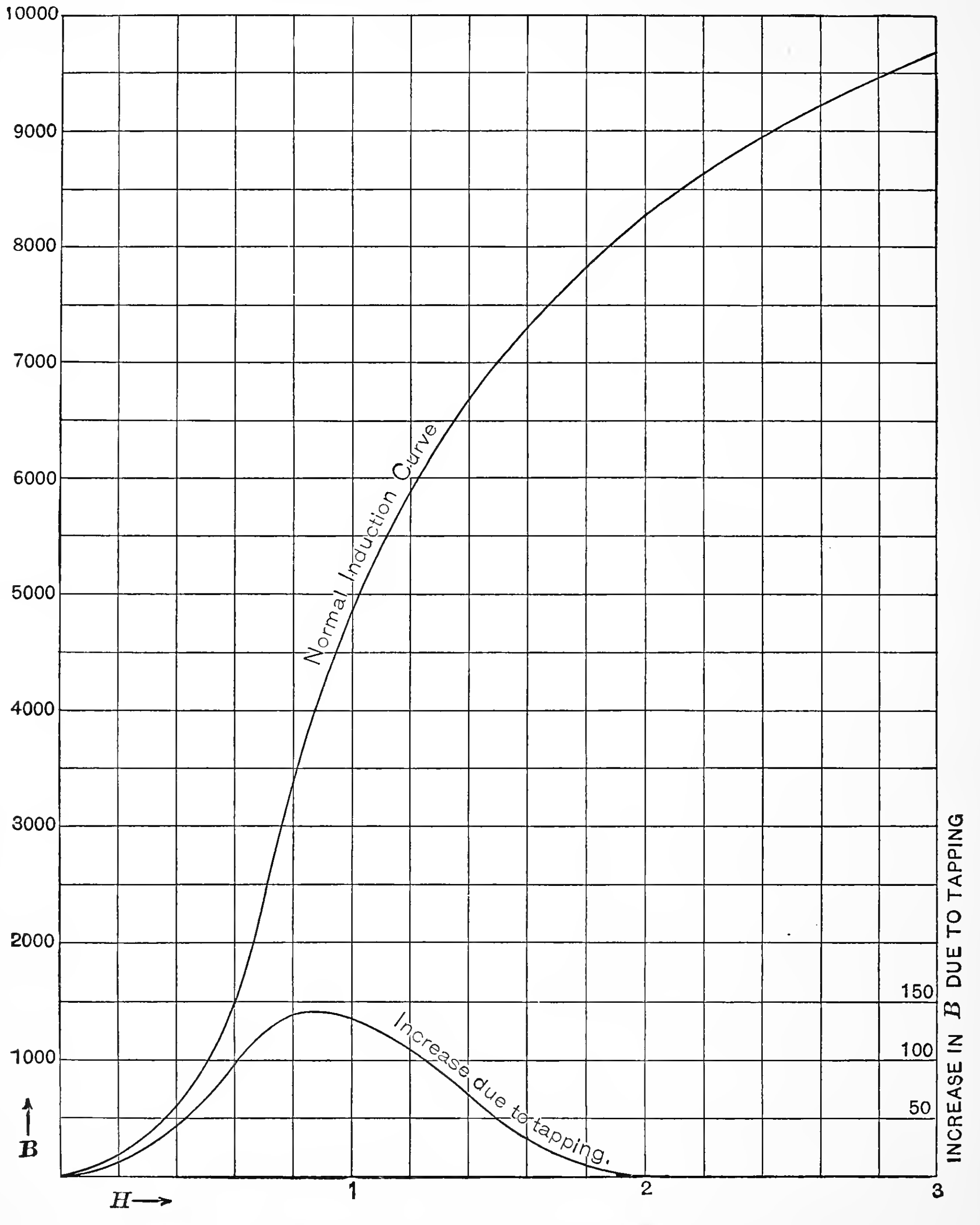

Fig. 26.—*Showing the influence of gentle vibrations on the inductions in soft iron.* (Numerical data in Table XXX.)

reason to suppose was unusual the permeability as measured during a mechanical vibration assumed the enormous value of 80,000. These same phenomena are observed in hard iron and steel, but to a much less degree.

GENTLE VIBRATIONS.

The following experiment was undertaken to determine whether the ordinary vibrations of a building containing moving machinery, such as a reciprocating engine, affect the values obtained in a magnetic test. The gong was removed from a small electric bell and the electromagnet mounted so that the hammer might strike against one end of a slender wooden rod 50 centimeters long, the other end of which rested against one of the yokes containing the test specimen. The wooden rod was interposed partly to deaden the effect of the blows delivered by the hammer and partly to permit the removal of the electromagnet to such a distance that its field would not react on the test specimen. To diminish the vibration still further a piece of soft rubber tubing was slipped over the hammer and another piece fastened to the end of the wooden rod. To insure a separation of the natural vibrations of the building from those of the experiment, the magnetic system under test was mounted on several layers of heavy wool felt. As nearly as could be estimated, by placing the hand alternately on the apparatus under test and on the table, the tapping device gave a disturbance of the same order of of magnitude as the vibration of the building. With this arrangement the data of Table XXX were obtained. The first column gives the magnetizing force; the second, the value of the induction after the iron had been subjected to many reversals to insure a cyclic state; the third, the induction obtained while the iron was under vibration; the fourth, the increase due to vibration, and the last column gives the proportional increase. These data are shown graphically in Fig. 26. It is to be noticed that the effect of vibration, both in absolute value and in percentage, passes through a maximum at approximately the point where the differential permeability is a maximum. The maximum value of 7 per cent in the disturbing effect shows that for accurate work it is necessary to protect the apparatus from vibration. Even the slamming of a door at one time and the dragging of a heavy box along the floor at another have modified the induction by a measurable amount.

Small changes in the intensity of the mechanical disturbance were accompanied by correspondingly small changes in magnetism, so that the curve may be taken as that characteristic of small disturbances.

To investigate more fully the nature of the effect of these mechanical vibrations the specimen was subjected without vibrations to many reversals of a small force until a cyclic state ensued and the ballistic throw on reversal noted. Next, without altering the current, the vibrator was started. This produced a small deflection. The return reversal was then taken without vibration, then another reversal without vibration, then the tapping, and lastly a reversal while the tapping was in progress. The following table shows the results:

Operations performed		Galvanometer
Magnetic.	Mechanical.	Deflection.
Reversal.	None.	+7.00
None.	Tapping.	+ .23
Reversal.	None.	−7.28
Reversal.	None.	+7.00
None.	Tapping.	+ .29
Reversal.	Tapping.	−7.47

The small deflection produced by tapping after a reversal had been made was the result of the first few taps, for an instantaneous closing of tapping circuit produced the full effect which was not increased by repeated and continued tapping. It is also characteristic that a single reversal wipes out the effect of previous tapping so that the second reversal is normal. What occurs may be shown more clearly by the use of Fig. 28. Here A represents the magnetic state before the first throw. The first reversal brings the state point to B. Tapping runs it up to D. A reversal without tapping brings it back to A. Tapping runs it down to C. Reversal with tapping carries it to D. So that simple reversals cause the state point to traverse cycle AB. Reversals with taps give cycle CD. Reversals followed by taps give cycle CBDA.

A comparison of these effects with those noted under the study of viscosity shows a close connection between the creeping up of the induction due to viscosity and the same thing for tapping. Both these phenomena may be accounted for by assuming a frictional force opposing the movements of the molecular magnets. It was found that such gentle vibrations as these were of little help in demagnetizing either when used alone or with current.

For higher inductions the effect of tapping was appreciable but negligible.

The persistance of previous polarization, as modified by a slight tapping, is shown in the data of Table XXXI. Here the iron has been polarized and then subjected to reversals of a small force till a cyclic condition exists. A few taps raise the apparent induction, which then decreases to a second constant value somewhat higher

TABLE XXXI.

Showing the demagnetizing effect of tapping combined with repeated reversals.

Number of reversal	Galvanometer deflection
1	9.80
2	6.19
3	5.99
4	5.81
6	5.71
8	5.66
10	5.62
20	5.62
100	5.61
200	5.62
202	5.80 after gentle tapping for 15 seconds
204	5.86 " " " " 1 minute
206	5.89 " " " " 2 "
306	5.89 " " " " 100 cycles
406	5.69
500	5.69
1800	5.69

than the first. The gentle vibration has therefore removed a portion of the residual induction, but is not an efficient means of demagnetization.

From the preceding experiment it appears desirable that the magnetic system be protected from small mechanical vibrations. A pad of felt half an inch thick accomplishes this very nicely for all ordinary cases.

INFLUENCE OF TEMPERATURE.

It is well known that for a small rise of temperature above room values the permeability of iron increases for low inductions and

TABLE XXXII.

Showing the induction at various temperatures of an annealed transformer iron ring.

H	B_8 $t=8$	B_{26} $t=26.5$	B_{48} $t=48$	$B_{48}-B_8$	$\frac{B_{48}-B_8}{40}$	$\frac{B_{48}-B_8}{40\ B_8}$
0.5	473	495	516	43	+1.1	.0023
1.0	3317	3479	3621	304	+7.6	.0023
2.0	8810	8970	9170	360	+9.0	.0010
3.0	11560	11700	11870	310	+7.7	.0007
5.0	14330	14460	14510	180	+4.5	.0003
10.0	16440	16440	16440	0	0	.0000
15.0	17150	17160	17180	30	0	.0000

See Fig. 27.

TABLE XXXIII.

Showing the inductions at various temperatures of an unannealed transformer iron ring.

H	B_{12} $t=12$	B_{47} $t=47$	$B_{47}-B_{12}$	$\frac{B_{47}-B_{12}}{35}$	$\frac{B_{47}-B_{12}}{35\ B_{12}}$
0.5	290	306	16	.5	.0017
1.0	1081	1148	67	1.9	.0018
2.0	4670	4800	130	3.7	.0008
3.0	7225	7310	85	2.4	.0003
5.0	10290	10340	50	1.4	.0001
10.0	13930	12920	—10	— .3	.0000
15.0	15630	15590	—40	—1.1	.0000

See Fig. 27.

decreases for high inductions. At higher temperature this temperature coefficient is always negative and increases rapidly with the temperature, until finally the iron becomes practically nonmagnetic

at some temperature between 690° C. and 870° C. For the ordinary fluctuations of room temperature very little experimental work has been done.

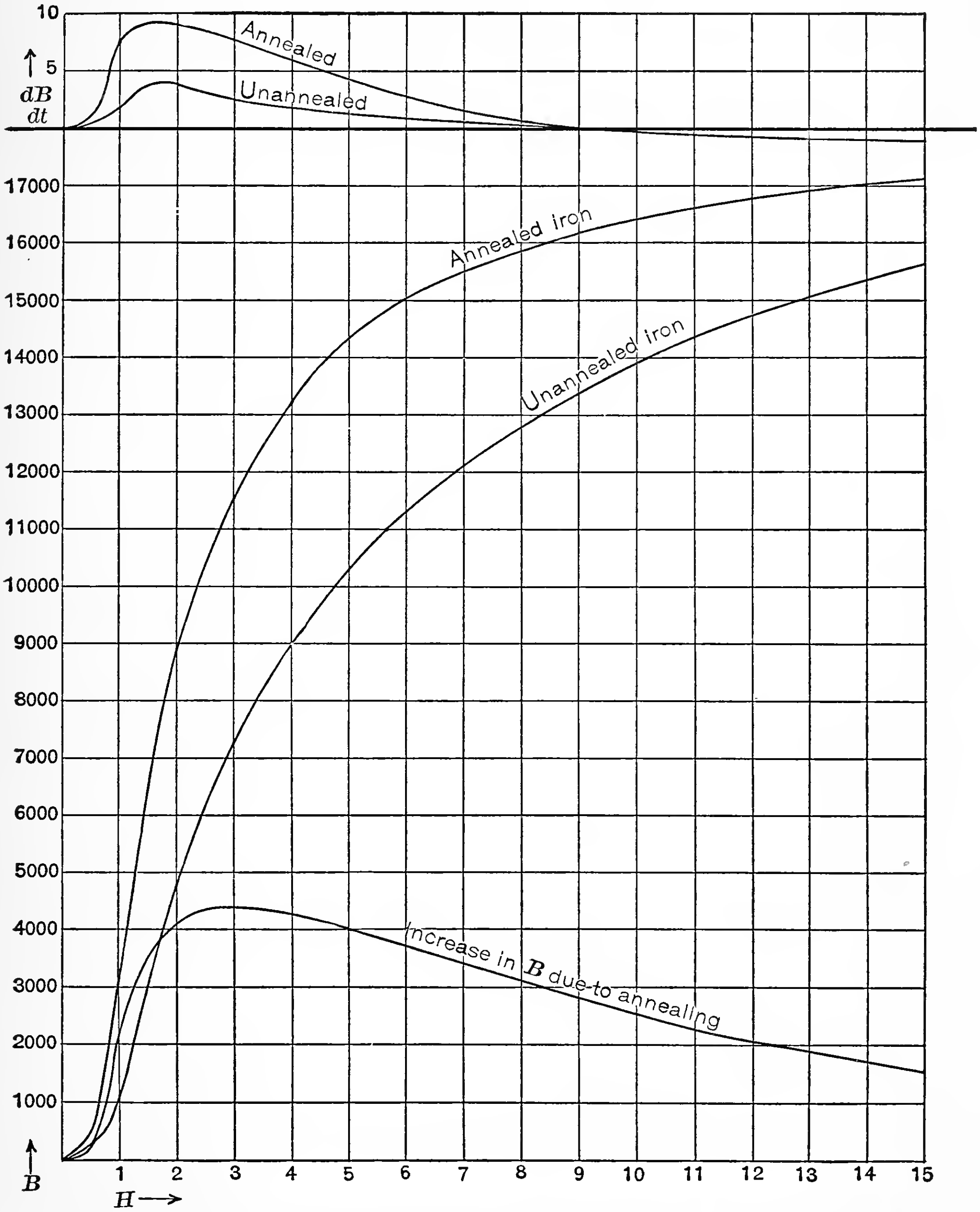

Fig. 27.—*Showing the effect of temperature and annealing on the induction in soft iron.*

(Numerical data in Tables XXXII, XXXIII, and XXXIV.)

Ewing,[19] from data obtained at 7° and 100° C., concluded that atmospheric fluctuations need not be considered in magnetic meas-

[19] Magnetic Induction, etc., p. 178.

urements. Permanent magnets such as are used in magnetic surveys and in electrical measuring instruments have a negative temperature coefficient of the order of .05 per cent. Whether or not the temperature coefficient is of sufficient importance to warrant its consideration is a question of the degree of accuracy desired. It seemed worth while therefore to determine the temperature coefficients of a few specimens over the atmospheric range. Four different specimens of transformer iron were examined at different temperatures. A portion of the data is shown numerically in Tables XXXII, XXXIII, and XXXIV, and graphically in Fig. 27. These specimens were two bundles of stamped transformer iron rings about 10 centimeters in diameter, cut from the same sheet. One was annealed and the other not. From the data and curves the following observations may be made:

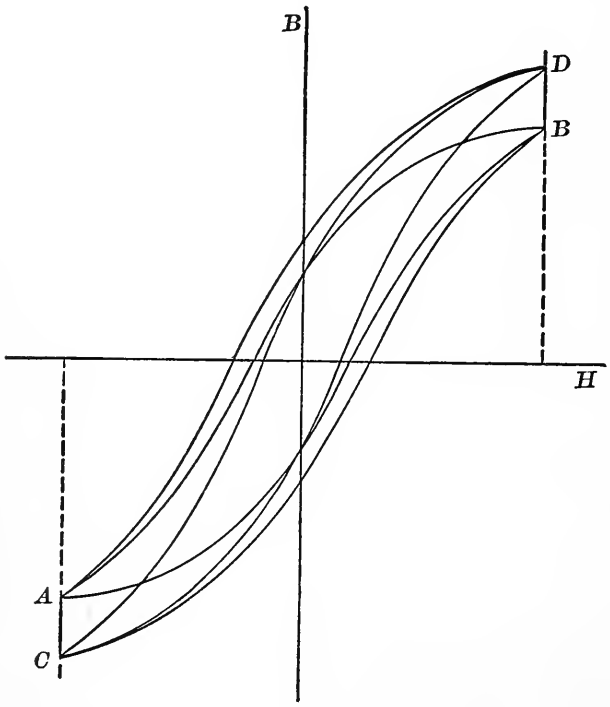

Fig. 28.—*Ideal curve to illustrate the effect of vibration on the apparent induction.*

(1) The change in induction per 1° C. rise in temperature is greatest in the neighborhood of the maximum permeability.

(2) The temperature coefficient is greater for the annealed than for the unannealed iron.

(3) The high value of this maximum temperature coefficient (one-fourth per cent) shows that temperature must be taken account of if an accuracy of 1 per cent is to be attained.

(4) The increase of induction due to annealing is greatest near the point of maximum permeability.

Throughout this work one is impressed with the varying sensitiveness with which the different parts of the *B–H* curve are influenced by slight changes in the conditions. All those elements, such as polarization, temperature, viscosity, or vibrations, which

tend to modify the apparent induction produce their greatest effects in the steep part of the induction curve. Beyond the critical point the induction is independent of previous magnetization and but lightly influenced by vibrations and temperature changes. Greater sensitiveness is noticed in the soft irons than in the hard ones. The difficulties of permeability measurements, therefore, are found in the earlier part of the induction curve, and it is here that the greatest care must be taken and the largest tolerance allowed.

TABLE XXXIV.

Showing the effect of annealing on the induction in transformer iron (Temperature 10°C). Calculated from Tables XXXII and XXXIII.

H	Annealed=B_a	Unannealed=B_u	B_a-B_u	$\frac{B_a-B_u}{B_a}$
0.5	475	289	186	.39
1.0	3332	1078	2254	.67
2.0	8830	4660	4170	.47
3.0	11580	7220	4360	.38
5.0	14340	10290	4050	.28
10.0	16440	13930	2510	.15
15.0	17150	15630	1520	.09

See Fig. 27.

THE BEST METHOD OF PROCEDURE.

In view of evidence offered in the preceding pages the following rule may be outlined as the best (ballistic) method of procedure in magnetic testing:

The magnetic system, consisting of the test pieces and the connecting yokes, should be mounted with its plane perpendicular to the earth's field. If necessary the system should be protected from mechanical vibrations by means of a pad of felt, or something equivalent. If an accuracy of 1 per cent in the steep part of the B–H curve is desired the temperature should be kept at some standard temperature (e. g., 20° C.) constant to 1° or 2° C. It is not feasible to apply a temperature coefficient correction on account of the difficulty in getting its value.

The demagnetization should be accomplished by a current reversed at the rate of approximately one cycle per second, while gradually diminished in such a way that the rate of decrease of the induction is as nearly as may be uniform. An ammeter in circuit and a rough estimate of the shape of the *B–H* curve will enable one to regulate the rate of decrease of current with sufficient exactness. The initial demagnetizing current should be sufficient to carry the induction beyond the knee of the *B–H* curve,[20] and the final current should be not greater than the smallest magnetizing current to be used.

The full demagnetization may be accomplished in about ninety seconds.

Now apply the lowest magnetizing force desired and reverse at the same speed as in demagnetizing. At intervals get a ballistic deflection. Continue this until two deflections about twenty-five reversals apart show only a negligible difference[21]. This final deflection is the normal induction.

Without demagnetizing again, apply the next larger magnetizing force and reverse as before. Continue in this way till all the required points on the curve have been obtained.

In closing I wish to acknowledge my indebtnesss to Professor Rosa, under whose supervision the work has been done, for his continued advice and suggestions.

WASHINGTON, September 3, 1907.

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[20] Without going to the trouble of a preliminary test an initial demagnetizing force of 15 units may safely be assumed for all specimens of soft iron.

[21] Several hundred reversals may be required in the steep part of the *B–H* curve, while half a dozen are sufficient in the upper portions.